

Observation of χ_b and χ_b' Production in Exclusive
Decays of the T' and T'' with the
CUSB Detector at the Cornell e^+e^- Storage Ring

Dissertation
der
Fakultät für Physik
der
Ludwig-Maximilians-Universität München

vorgelegt von Gerald Eigen
aus Göttingen

München, den 12. September 1984

ZUSAMMENFASSUNG 1
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ZUSAMMENFASSUNG

In dieser Arbeit wird über die erstmalige Beobachtung der 1^3P und 2^3P Zustände im Bottomonium System berichtet. Die Untersuchung der $b\bar{b}$ -Zustände ist fundamental für das Verständnis der starken Wechselwirkung und deren Beschreibung durch die Quantenchromodynamik. Auf Grund der schweren b-Quark Masse erwartet man, daß nicht-relativistische Potentialmodelle gute Voraussagen für das Bottomonium System liefern. Durch genaue Messungen des reichhaltigen $b\bar{b}$ -Spektrums lassen sich die verschiedenen Voraussagen überprüfen, Erkenntnisse über das Quark-Antiquark Potential gewinnen sowie die starke Kopplungskonstante α_s und den QCD Skalenparameter $\Lambda_{\overline{MS}}$ bestimmen. Eine genaue Analyse der 3P -Zustände ermöglicht insbesondere, neue Erkenntnisse über die Spin-abhängigen Wechselwirkungen zu erlangen.

Die 1^3P und 2^3P Zustände, auch χ_b bzw. χ_b' genannt, sind vor kurzem mit Hilfe des CUSB Detektors am Cornell Elektronen Speicherring CESR entdeckt worden. Untersucht wurden einerseits die exklusiven Zerfallskanäle $T' \rightarrow \gamma \chi_b \rightarrow \gamma \gamma T \rightarrow \gamma \gamma (\mu^+ \mu^-)$, $T' \rightarrow \gamma \chi_b' \rightarrow \gamma \gamma T' \rightarrow \gamma \gamma (\mu^+ \mu^-)$ und $T' \rightarrow \gamma \chi_b' \rightarrow \gamma \gamma T \rightarrow \gamma \gamma (\mu^+ \mu^-)$ sowie andererseits die inklusiven Übergänge $T' \rightarrow \gamma + X$ und $T'' \rightarrow \gamma + X$. Der nicht magnetische CUSB Detektor, ein Kalorimeter, das im wesentlichen aus NaI Kristallen besteht, eignet sich besonders gut für diese Messungen, da Photonen mit guter Energieauflösung nachgewiesen werden. Insgesamt wurden ~ 170000 Resonanzzerfälle am T' und ~ 50000 Resonanzzerfälle am T'' analysiert.

Im T' Datensatz wurden 134 exklusive $\gamma\gamma$ Ereignisse mit einem e^+e^- oder $\mu^+\mu^-$ Paar im Endzustand gefunden. Ca. 40% dieser Ereignisse zeigen eine Anhäufung bei (125,425) MeV im $\gamma\gamma$ Energiekorrelationsspektrum. Im Spektrum für das niederenergetische Photon sind zwei aufgelöste Linien mit Positionen bei (106 ± 3) und (128 ± 2) MeV zu sehen. Diese Ergebnisse lassen sich bereits als Evidenz für χ_b -Produktion in radiativen T' -Zerfällen interpretieren. Im inklusiven Photonspektrum wurde ebenfalls im Energiebereich von 100-160 MeV ein deutliches Signal von 3100 Photonen über dem Untergrund beobachtet. Nach Subtraktion des Untergrundes (von $\pi^0 \rightarrow 2\gamma$ Zerfällen) wurden drei getrennte Linien mit Positionen bei (108 ± 2) , (128 ± 3) , und (149 ± 5) MeV gefunden. Für die beiden unteren Linien stimmen die Positionen mit denen im exklusiven Spektrum gut überein. Die dritte Linie ist im Photonspektrum der inklusiven Übergänge auf Grund der großen hadronischen Breite des 1^3P_0 Zustandes unterdrückt.

Im $\mathbf{T}'$ Datensatz wurden 84 exklusive $\gamma\gamma\mu^+\mu^-$ und $\gamma\gamma e^+e^-$ Ereignisse gefunden, von denen $\sim 50\%$ im $\gamma\gamma$ Energiekorrelationsspektrum eine Anhäufung bei (100,230) MeV bzw. (100,760) MeV zeigen. Die Analyse des Energiespektrums für das niederenergetische Photon dieser Signalereignisse führte zur Beobachtung von zwei, allerdings nicht voll aufgelösten Linien mit Positionen bei (84 ± 3) und (99 ± 2) MeV. Diese Resultate werden als Evidenz für λ_b' -Produktion in radiativen $\mathbf{T}'$ -Zerfällen angesehen. Im inklusiven Photonspektrum, das ein Signal von 2200 Photonen im Energiebereich von 80-130 MeV zeigte, wurden 3 ebenfalls nicht vollkommen getrennte Linien gefunden. Die Positionen der beiden unteren Linien von (84 ± 2) und (101 ± 3) MeV sind in guter Übereinstimmung mit denen im exklusiven Spektrum. Die dritte Linie, die im Spektrum der exklusiven Ereignisse aus gleichem Grund wie im $\mathbf{T}'$ Datensatz nicht zu sehen ist, liegt bei (122 ± 5) MeV.

Aus den beobachteten Linienpositionen wurden die Massen der einzelnen λ_b und λ_b' Zustände bestimmt:

$$\begin{aligned} M(1^3P_0) &= (9873\pm 5) \text{ MeV}, & M(1^3P_1) &= (9894\pm 2) \text{ MeV}, & M(1^3P_2) &= (9915\pm 2) \text{ MeV} \\ M(2^3P_0) &= (10233\pm 5) \text{ MeV}, & M(2^3P_1) &= (10256\pm 2) \text{ MeV}, & M(2^3P_2) &= (10271\pm 2) \text{ MeV}. \end{aligned}$$

Die Massenschwerpunkte liegen bei $M(1^3P_{\text{cog}}) = (9904\pm 1.5) \text{ MeV}$ und $M(2^3P_{\text{cog}}) = (10262\pm 1.5) \text{ MeV}$. Für λ_b - und λ_b' -Produktion in den inklusiven Übergängen $\mathbf{T}' \rightarrow \gamma\lambda_b$ und $\mathbf{T}' \rightarrow \gamma\lambda_b'$ wurden Verzweigungsverhältnisse von $(15.5\pm 2.5)\%$ und $(35.9\pm 3)\%$ ermittelt. Für die exklusiven Übergänge ergaben sich Produktverzweigungsverhältnisse von:

$$\begin{aligned} \sum_J \text{BR}(\mathbf{T}' \rightarrow \gamma 1^3P_J) \cdot \text{BR}(1^3P_J \rightarrow \gamma \mathbf{T}) &= (3.2\pm 0.7)\%, \\ \sum_J \text{BR}(\mathbf{T}' \rightarrow \gamma 2^3P_J) \cdot \text{BR}(2^3P_J \rightarrow \gamma \mathbf{T}') &= (5.0\pm 2.1)\% \\ \sum_J \text{BR}(\mathbf{T}' \rightarrow \gamma 2^3P_J) \cdot \text{BR}(2^3P_J \rightarrow \gamma \mathbf{T}) &= (3.6\pm 1.1)\% \end{aligned}$$

In den Daten der exklusiven $\gamma\gamma\mu^+\mu^-$ und $\gamma\gamma e^+e^-$ Ereignisse vom $\mathbf{T}'$ wurden je zwei Kandidaten gefunden, die mit dem Übergang $\mathbf{T}' \rightarrow \gamma 1^3P_J \rightarrow \gamma\gamma \mathbf{T}$ konsistent sind. Ferner wurden zwei Ereignisse für den multiplen Kaskadenübergang $\mathbf{T}' \rightarrow \gamma\lambda_b' \rightarrow \gamma\gamma \mathbf{T}' \rightarrow \gamma\gamma\gamma\lambda_b \rightarrow \gamma\gamma\gamma\gamma(\mathbf{T} \rightarrow ee)$ sowie 4 Ereignisse für $\mathbf{T}' \rightarrow \gamma\lambda_b' \rightarrow \gamma\gamma \mathbf{T} \rightarrow \gamma\gamma\pi^+\pi^-(\mathbf{T} \rightarrow e^+e^-)$ beobachtet.

Unsere Ergebnisse für λ_b -Produktion sind in anderen Experimenten bestätigt worden. Die Resultate für λ_b - und λ_b' -Produktion stimmen gut mit theoretischen Vorhersagen von Potentialmodellen überein. Die besten Vorhersagen liefern solche Modelle, die explizit auf der QCD basieren und Spin-unabhängige relativistische Korrekturen berücksichtigen.

ABSTRACT

The nonmagnetic CUSB detector at the Cornell Electron Storage Ring (CESR) has been used to study both the exclusive cascade decays $\mathbf{T}' \rightarrow \gamma \lambda_b \rightarrow \gamma \gamma \mathbf{T} \rightarrow \gamma \gamma (\mu^+ \mu^- \text{ or } e^+ e^-)$, $\mathbf{T}'' \rightarrow \gamma \lambda_b' \rightarrow \gamma \gamma \mathbf{T}' \rightarrow \gamma \gamma (\mu^+ \mu^- \text{ or } e^+ e^-)$, $\mathbf{T}'' \rightarrow \gamma \lambda_b' \rightarrow \gamma \gamma \mathbf{T} \rightarrow \gamma \gamma (\mu^+ \mu^- \text{ or } e^+ e^-)$ and the inclusive photon spectra from radiative $\mathbf{T}'$ and $\mathbf{T}''$ decays. In a data sample of $\sim 170,000$ $\mathbf{T}'$ resonance decays and $\sim 50,000$ $\mathbf{T}''$ resonance decays evidence for λ_b and λ_b' production has been found in both analyses. From the line positions in the photon spectra the λ_b masses have been determined to be at $M(1^3P_0) = (9,873 \pm 5)$ MeV, $M(1^3P_1) = (9,894 \pm 2)$ MeV and $M(1^3P_2) = (9,915 \pm 2)$ MeV, the λ_b' masses at $M(2^3P_0) = (10,233 \pm 5)$ MeV, $M(2^3P_1) = 10,256 \pm 2$ MeV and $M(2^3P_2) = (10,271 \pm 2)$ MeV. The spin-averaged center-of-gravities have been obtained at $M(1^3P_{\text{cog}}) = (9,904 \pm 1.5)$ MeV and $M(2^3P_{\text{cog}}) = (10,262 \pm 1.5)$ MeV. The product branching ratios for the three exclusive decay modes are $(3.2 \pm 0.7)\%$, $(5.0 \pm 2.1)\%$ and $(3.6 \pm 1.1)\%$, respectively. For the inclusive transitions $\mathbf{T}' \rightarrow \gamma \lambda_b$ and $\mathbf{T}'' \rightarrow \gamma \lambda_b'$, branching ratios of $(15.5 \pm 2.5)\%$ and $(35.9 \pm 3)\%$ have been measured. The results are in good agreement with predictions of potential models based on perturbative QCD.



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I. INTRODUCTION

The Υ family was discovered at Fermilab in the spring of 1977, three years after the discovery of the ψ family which proved the existence of the charm quark and caused a revival of the quark model. In the dimuon mass spectrum, produced with the 400 GeV proton beam in the reaction $pN \rightarrow \mu^+ \mu^- + X$, a clear bump at 9.5 GeV and a shoulder around 10 GeV were observed [He 77]. The best fit of the spectrum favored 3 resonances with peak positions at masses of 9.4, 10.0 and 10.4 GeV. These resonances, labelled Υ , Υ' , and Υ'' , were interpreted as quark-antiquark ($q\bar{q}$) bound states of a new heavy fifth quark, the b quark, with a predicted charge $e_b = -1/3$ and carrying a new quantum number 'bottom' or 'beauty'. This interpretation followed in analogy with the description of the J/ψ and ψ' as bound states of a charm quark and its antiquark.

In 1978, the Υ and Υ' were confirmed as narrow resonances by different groups at the DORIS storage ring in the process $e^+e^- \rightarrow \text{hadrons}$ [Be 78, Da 78, Bi 78, Hh 79]. Masses and partial leptonic widths Γ_{ee} were determined from the measured resonance cross sections. The dilepton branching ratio for $\Upsilon \rightarrow \mu^+ \mu^-$ was measured and hadronic decays of the resonances were studied. In particular, the data for the leptonic widths $\Gamma_{ee}(\Upsilon)$ and $\Gamma_{ee}(\Upsilon')$ supported the hypothesis of a quark charge $|e_b| = 1/3$ [Ni 81].

In 1979 the Cornell e^+e^- storage ring (CESR) started operation. Besides seeing the Υ and Υ' with much better resolution than at DORIS, the Υ'' was observed as a sharp resonance by both detectors, CLEO and CUSB operating at CESR. In addition a fourth broad resonance, the Υ''' , was discovered. Its large width of 20 MeV compared to the 4.6 MeV machine energy spread, being about 1000 times larger than the widths of the narrow resonances, indicated that this state already lies above the free b-flavor threshold ($B\bar{B}$ threshold).

In accord with predictions of $q\bar{q}$ models all four resonances are 3S states and belong to the same meson family. While the three narrow resonances are $b\bar{b}$ bound states, the Υ''' is only a quasibound state allowing a dissociation into B-mesons, i.e. states composed of a b-quark and a light $\bar{u}$ - or $\bar{d}$ -quark thus carrying a non-zero beauty quantum number. However, besides 3S states, $q\bar{q}$ models also predict other $b\bar{b}$ bound states like 3P , 1S etc. to exist. The states are expected to be visible in electromagnetic or hadronic transitions from energetically higher lying 3S states. The present thesis describes the observation of 1^3P and 2^3P states in the exclusive

reactions $T' \rightarrow \gamma 1^3P \rightarrow \gamma \gamma T$ and $T'' \rightarrow \gamma 2^3P \rightarrow \gamma \gamma T(T')$ where the final $T(T')$ state subsequently decays into an e^+e^- or $\mu^+\mu^-$ pair.

The 1^3P and 2^3P states, called χ_b and χ_b' , respectively, were recently observed for the first time with the CUSB detector at CESR. In two running periods $\sim 170,000$ resonance decays above continuum at the T' and $\sim 50,000$ events at the T'' were accumulated. Evidence for both χ_b and χ_b' production was found in two independent analyses using different data samples: In the inclusive photon spectrum obtained from analyzing hadronic decays of the T' and T'' and in the exclusive decay modes discussed in this thesis. In the inclusive photon spectrum one expects high statistics because the predicted branching ratios are relatively large: $BR(T' \rightarrow \gamma \chi_b) \approx 15\%$ and $BR(T'' \rightarrow \gamma \chi_b') \approx 30\%$. However, the background is also very large due to $\pi^0 \rightarrow \gamma \gamma$ contributions in hadronic events. In the exclusive reactions the expected number of events is small because the multiplication of three BR's results in small product branching ratios of $BR(T' \rightarrow \gamma \gamma 1^+1^-) \approx .1\%$ and $BR(T'' \rightarrow \gamma \gamma 1^+1^-) \approx .21\%$. But on the other hand the background is very small.

In this thesis the analyses of the exclusive reactions will be discussed in greater detail while only the main features of the inclusive photon analyses are summarized. Results for masses of the individual χ_b and χ_b' states, fine splittings, and branching ratios determined from both analyses are presented. These results are compared with other measurements and theoretical predictions. The measurements of masses, fine splittings, and branching ratios for the $b\bar{b} \ ^3P$ states provide new experimental input for the study of quark-antiquark interactions, setting constraints on the various models. From the observed levels spacings of 3S and 3P states one can derive the exponent ν in an effective $q\bar{q}$ potential $V_{\text{eff}}(r) = ar^\nu$ (where a is a constant, see V.2.6). From the fine splittings one tests models for spin-dependent forces in the $q\bar{q}$ system. The branching ratios for transitions $^3P \rightarrow \gamma ^3S$ allow for a derivation of the strong coupling constant α_s .

The remainder of this chapter gives a further motivation for the study of the $b\bar{b}$ system. Chapter II gives a review on the phenomenology of heavy $q\bar{q}$ bound states discussing several potential models. Chapter III describes the Cornell Electron Storage Ring CESR and the present experiment. In chapter IV the data analysis for the individual exclusive decay modes is presented. Finally, chapter V concludes with the discussion of the results, a comparison of the results with theoretical predictions, and future

measurements which are necessary for a complete experimental study of the P states in bottomonium.

Motivation for $b\bar{b}$ Physics

The $b\bar{b}$ system is in many respects both an experimentally and theoretically interesting system to study. It is the heaviest known $q\bar{q}$ system. The b quark with a mass of ~ 5 GeV is a member of a new doublet in the classification scheme of quarks and leptons:

$$\begin{pmatrix} u \\ d \end{pmatrix}, \quad \begin{pmatrix} c \\ s \end{pmatrix}, \quad \begin{pmatrix} t \\ b \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} e \\ \nu_e \end{pmatrix}, \quad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}, \quad \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}.$$

For a complete scheme a sixth quark, the t quark, is expected to exist. However, up to now there is no experimental evidence for the existence of the t quark. According to the latest measurements at PETRA, the t quark mass must be heavier than 19 GeV.

The $b\bar{b}$ system allows the study of two different fundamental interactions: strong interactions described by Quantum Chromodynamics (QCD) for the $b\bar{b}$ bound states, and electroweak interactions described by the standard model [GWS 67] for B meson decays above the $B\bar{B}$ threshold. For masses below 10.5 GeV the b-quark and its antiquark form bound states (bottomonium). Since the quarks are very massive the binding force between them can be treated non-relativistically. In analogy to positronium the effective binding force is basically Coulombic generated by single gluon exchange. Ordinary quantum mechanics can be used to calculate energy levels, fine and hyperfine splittings, wave functions, transition rates, and decay rates (see discussion in chap. II.2).

Theoretical models of $q\bar{q}$ bound states have been very successful in the description of the charmonium spectrum. Since the b-quark is much heavier than the c-quark, the predictions are expected to be even more reliable for the bottomonium system. The spin 1/2 nature of the quarks determines the quantum numbers of the bound states while level spacings, fine and hyperfine splittings, wave functions and transition rates depend explicitly on the potential used.

Fig. 1.1 displays the level diagram for bottomonium in comparison to the level diagrams for charmonium and positronium. The bound states are classified in the standard spectroscopy notation by n^2S+1L_J . $n=1,2,3 \dots$ is the principle quantum number and labels the radially excited states. S is

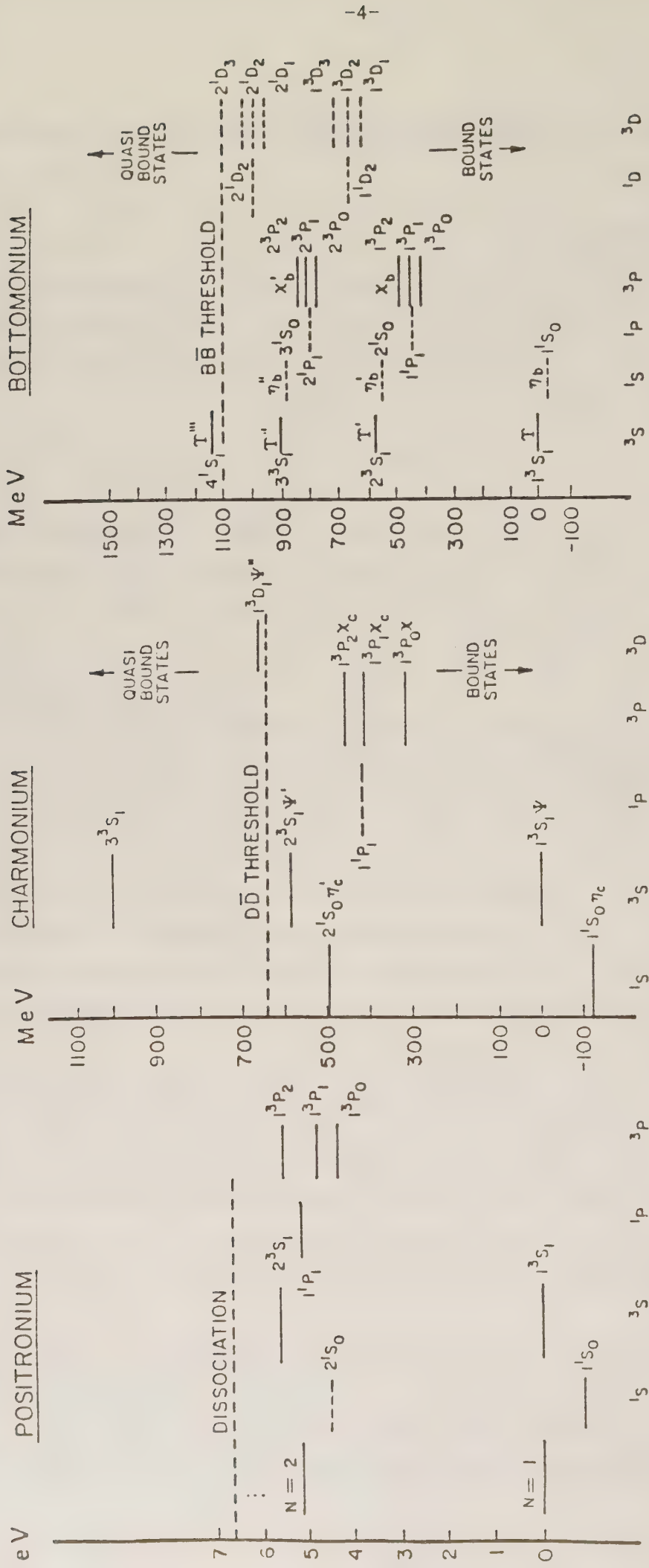


Fig. 1.1 Level diagrams for positronium, charmonium, and bottomonium. States which have not been observed are indicated by dashed lines. In the diagram for positronium the fine and hyperfine splittings have been magnified by a factor of ~ 1000 for reasons of representation.

the quantum number for the total spin of both quarks and takes values 0 or 1 corresponding to singlet or triplet states, respectively. L is the orbital angular momentum quantum number, where $L=0,1,2 \dots$ corresponds to the conventionally labelled S-wave, P-wave, D-wave etc. contributions, and $J=L+S$ is the total angular momentum quantum number. In this notation the four observed Υ resonances are triplet S-states, where the Υ is the ground state 1^3S_1 , and the $\Upsilon', \Upsilon'', \Upsilon'''$ are the radially excited states $2^3S_1, 3^3S_1$ and 4^3S_1 , respectively, the 4^3S_1 being already above the $B\bar{B}$ threshold. 22 bound states (S,P,D) are predicted for $b\bar{b}$ system, while only 8 bound states are expected for charmonium. Already 9 bound states have been discovered in bottomonium (all predicted 3S_1 and 3P_J states). In charmonium, all bound states except the 1^1P_1 states have been found. Positronium has, in principle, an infinite number of bound states, but the higher lying excited states are hardly accessible to experiments. So far 7 positronium states have been observed [Bo 80]. Therefore bottomonium might in fact become the best understood particle-antiparticle bound system in physics. Table 1.1 summarizes for comparison the relevant parameters of all three systems.

A rich spectrum of hadronic and electromagnetic transitions between bound states is predicted for the $b\bar{b}$ system (see figs 2.6 and 2.8). In e^+e^- collisions only 3S states can be produced directly since they carry the quantum numbers of the photon, $J^{PC}=1^{--}$ (where J is the angular momentum, P the parity, and C the charge conjugation), and have a non-vanishing wave function at the origin. However, transitions from the 3S states provide a way of producing new states ($^3P_J, ^1P_1, ^1S_0, ^3D_J$, and 1D_2 states). For example, in charmonium the 1S_0 and 3P_J states have been discovered in the inclusive photon spectrum from ψ' decays. The observation of these new states in the $b\bar{b}$ system is important for the study of spin-dependent interactions in the $q\bar{q}$ system.

Most dominant among the hadronic transitions are the $\pi\pi$ transitions between 3S states. The branching ratios have been measured to: $BR(\Upsilon' \rightarrow \pi^+\pi^-\Upsilon) = (18.8 \pm 1.0)\%$, $BR(\Upsilon'' \rightarrow \pi^+\pi^-\Upsilon') = (3.1 \pm 2)\%$, $BR(\Upsilon''' \rightarrow \pi^+\pi^-\Upsilon'') = (4.6 \pm 1.3)\%$. The $\pi\pi$ transition to the 1P_1 is expected to have a BR of $\sim 1\%$ [KY 81]. Other hadronic transitions are rather small. Among the electromagnetic transitions the electric dipole (E1) transitions are dominant with expected branching ratios in the order of a few percent. E1 transitions proceed via the emission of a single monochromatic photon, which changes the parity and orbital angular momentum ($\Delta L = \pm 1$) of the final state. Typical examples are the transitions $n^3S_1 \rightarrow \gamma n'^3P_J$ (with $3 \leq n > n' \geq 1$) and

Table 1.1 Comparison of Bottomonium with Charmonium and Positronium

	bottomonium	charmonium	positronium
constituent charge	$-1/3 e$	$2/3 e$	e
constituent mass [MeV]	~ 5000	~ 1500	$.511$
force	strong	strong	electromagnetic
coupling	$\alpha_s \sim .16$	$\alpha_s \sim .19$	$\alpha = 1/137$
underlying theory	QCD	QCD	QED
$\langle v^2/c^2 \rangle$	$\sim .08$	$\sim .3$	$\sim 1.3 \times 10^{-5}$
annihilation	gluons	gluons	photons
predicted bound states	22	8	∞
observed bound states	9	7	7
$\langle r^2 \rangle^{1/2}$ [cm]	2×10^{-14}	4×10^{-14}	10^{-8}
1^3S_1 Life time [s]	$\sim 10^{-20}$	$\sim 10^{-20}$	$\sim 1.4 \times 10^{-7}$
Mass (1^3S) [MeV]	9460	3070	1.02
binding energy E_b [MeV]	1200	800	6.8×10^{-6}

$m^3P_J \rightarrow \gamma m'^3S_1$ (with $2 \geq m \geq m' \geq 1$) discussed in this thesis. Magnetic dipole ($M1$) transitions, connecting states with identical L but different S are also expected to occur, but the predicted rates are very small (see chap. II.3)

All $b\bar{b}$ bound states decay dominantly via gluons into hadrons. Thus bottomonium provides a gluon factory. Gluons, the exchange particles of the strong interaction, are massless vector bosons carrying a color quantum number. Since $SU(3)$ is the underlying color symmetry group 8 different types of gluons are expected to exist in QCD. Gluons cannot exist as free particles since they carry a color quantum number while due to color confinement all physical observable states are colorless (color singlet). Therefore one can only study the gluon properties, like the gluon self coupling, by analyzing the decay modes, i.e. gluon jets. For example, the two gluon decays of the 3P_0 and 3P_2 states are very suited for this study (see V.4).

However, as predicted by QCD two gluons can form bound states, called glueballs. Bottomonium is a good place to search for glueballs because the Υ can decay into a photon plus a glueball or into two heavy glueballs, the latter mode forbidden by energy conservation for the J/ψ [Ty 82]. Other interesting decay modes are the rare Υ decays into a gamma plus an axion or a gamma plus a Higgs particle.

All bound state quantities, fine and hyperfine splitting, transitions and decay rates, involve couplings to gluons at least in the second order of the QCD expansion. Since in bottomonium theoretical uncertainties like relativistic effects, higher order QCD corrections and nonperturbative effects are much smaller than in charmonium the measurements of the $b\bar{b}$ bound state quantities allow a much more reliable determination of the strong coupling constant α_s and the QCD scale parameter $\Lambda_{\overline{MS}}$ than measurements of the $c\bar{c}$ bound state quantities.

Since bottomonium is a more non-relativistic system and has more bound states than charmonium, it is therefore the better system for studying QCD and plays a role similar to that of hydrogen atom in the development of quantum mechanics. Therefore bottomonium is often called 'the hydrogen atom of strong interactions'. In hydrogen the effective binding potential consists of a pure Coulomb potential plus the angular momentum term $L(L+1)/2\mu r^2$ (where μ is the reduced mass) allowing an easy calculation of energy eigenstates and wave functions with the Schrödinger equation. The



(c)

electron can occupy any of these states by absorbing or emitting a photon of discrete energy, giving rise to a very rich characteristic spectrum as shown in fig. 1.2. The analysis of this spectrum was therefore much more helpful in testing quantum mechanical predictions and determining the theory's fundamental constant, Planck's constant $\hbar$, and the fine structure constant $\alpha=e^2/\hbar c \approx 1/137$ than the study of complex atoms.

However, not only the $b\bar{b}$ bound states provide a study of exciting physics. Since the Υ''' decays to $\sim 100\%$ into B-mesons ^{+) this is a B-meson factory allowing the study of 'open beauty'. Because of the larger mass, higher lying states are expected to decay into $B^*\bar{B}(\bar{B}^*B)$, $B^*\bar{B}^*$, etc.. The B^* -mesons are expected to decay almost entirely into a gamma and a B-meson. The photon of approximately 50 MeV can be easily detected [Hn 84]. Since the B-meson decays weakly, where the b quark decays by the emission of a W boson into a c- or u-quark, one can determine the ratio of transition amplitudes, described by the Kobayashi-Maskawa matrix elements V_{ub} and V_{cb} , from analyzing the single electron spectrum at the Υ''' [Sp 81]. Further, one can search for flavor changing neutral currents ($b \rightarrow d$ or $b \rightarrow s$) which are forbidden by the standard model, by looking for lepton pairs of opposite sign in B-meson decays.}

Another interesting topic is the study of CP-violation in the $B^0\bar{B}^0$ mixing, by searching for like-sign leptons. Since the B^0 life time is relatively long $\tau_B=(1.2\pm.4\pm.3)\times 10^{-12}$ sec [Lo 83], the effect might be of the order of $\sim 1/2\%$.

^{+)The B-meson has been reconstructed recently by the CLEO group from the search for decay modes $B^-\rightarrow D^0\pi^-$, $B^0\rightarrow D^{*+}\pi^-$ and $\bar{B}^0\rightarrow D^0\pi^+\pi^-$, $\bar{B}^0\rightarrow D^{*+}\pi^-\pi^-$. A mass of $(5274.2\pm 1.9\pm 2)$ MeV for the neutral and $(5270.8\pm 2.3\pm 2)$ MeV for the charged B-meson has been determined [Be 83].}

II. PHENOMENOLOGY OF HEAVY $q\bar{q}$ STATES

II.1 Properties of the T States

Electron positron collisions are well suited for the study of heavy $q\bar{q}$ states, as the initial state is well defined. The annihilation proceeds at rest into a virtual photon of mass $M = 2E_b = \sqrt{s}$ where E_b is the electron (positron) beam energy and s the total energy squared. Hence center-of-mass (CM) frame and laboratory frame are identical. The final state has to conserve the photon quantum numbers $J^{PC} = 1^{--}$. The virtual photon, coupling to the charges of quarks or leptons, usually creates a quark-antiquark or lepton-antilepton pair, as shown by the lowest order Feynman diagrams in fig. 2.1. This reaction mechanism involving QED processes and hadron production from two quark jets is present at any CM energy and comprises the continuum. A detailed discussion of the continuum process can be found in references [Fr 82, Wi 80].

However, the virtual photon can also couple directly to vector mesons (fig. 2.3), i.e. $q\bar{q}$ bound or quasi-bound states with the quantum numbers of the photon, whenever the CM energy is at the mass of such a vector meson. This reaction mechanism then becomes the dominant process producing resonances in the total cross-section at $\sqrt{s}=M_V$. For example in the hadronic cross section the well known low energy vector mesons ρ , ω , and ϕ as well as the heavy ψ and T states show up as sharp resonances (see fig. A.1 in appendix A). Figure 2.2 shows the four T resonances in the normalized hadronic cross-section measured with the CUSB detector. The observed widths of the narrow resonances T , T' , and T'' are given by the machine energy spread. The natural widths are about two orders of magnitude smaller. On the other hand, the observed width of the T''' is close to its natural width.

The relevant parameters which characterize the resonances are their masses and leptonic widths. The masses are obtained from the observed resonance position. For the narrow T states the data have been fitted to three gaussians including a correction term for the radiative tail above a continuum level which decreases as $1/s$. The widths have been fixed to the beam energy spread at the corresponding CM energy. For the T a mass of 9433 MeV was obtained at CESR. The systematic uncertainty in the energy scale, resulting from the measurements of currents in the magnets which provide the guide fields, was estimated to be ~ 30 MeV. At DORIS the T mass was measured to 9460 MeV with a systematic uncertainty of 10 MeV. To determine the

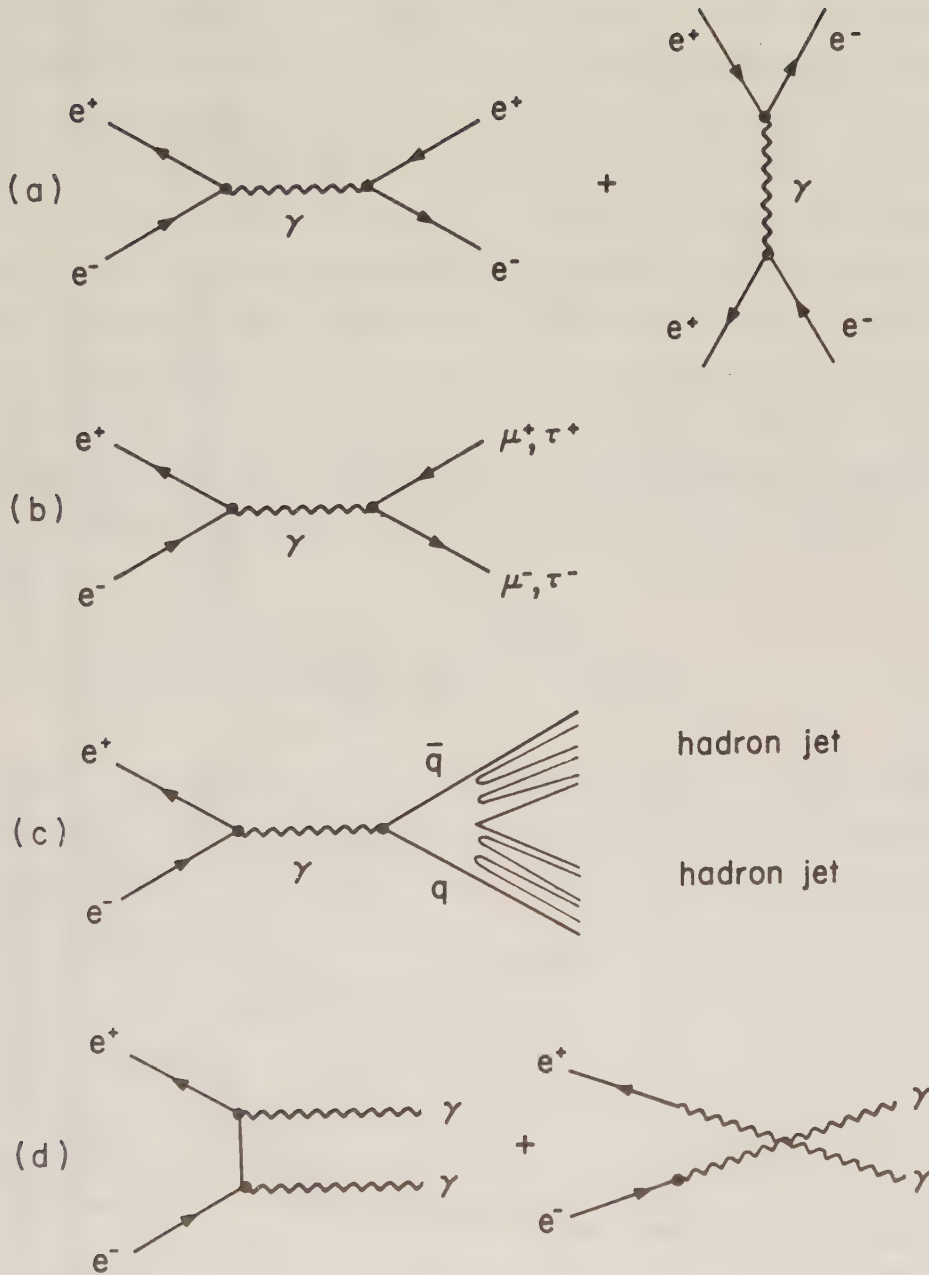


Fig. 2.1 Lowest order Feynman graphs for a) Bhabha scattering, b) $\mu(\tau)$ -pair production, c) hadron production, and d) two photon annihilation.

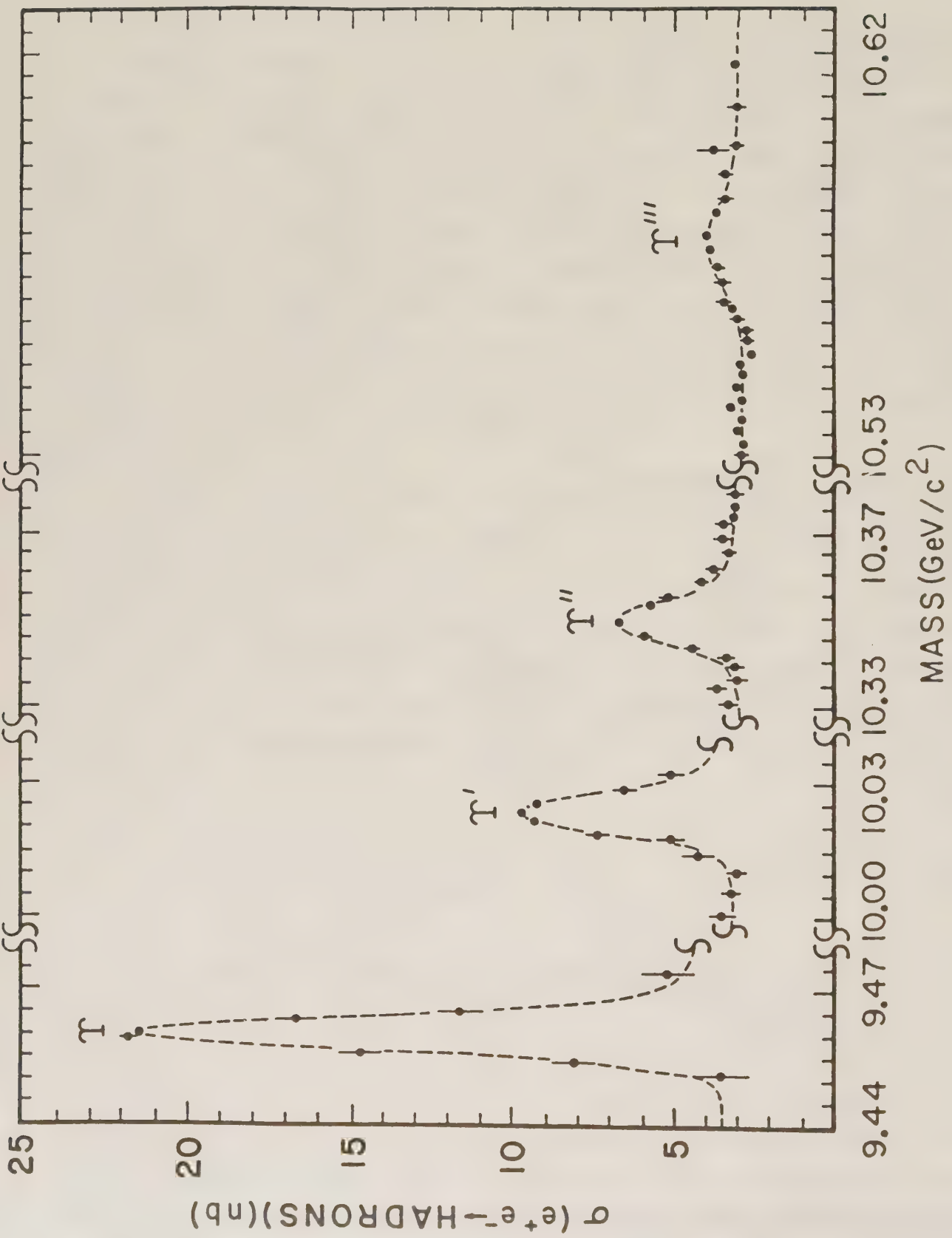


Fig. 2.2 Visible hadronic cross-section in the τ region (CESR energy scale).

absolute energy scale, high precision measurements using the beam depolarization method have been recently carried out at VEPP4 (in Novosibirsk), DORIS, and CESR. All three experiments confirmed the DORIS energy scale to be correct. Table 2.1 lists the masses for the Υ states obtained by different experiments. The high precision measurements are marked by an asterisk. The masses measured by CLEO and CUSB have been scaled upward by 0.28% to be in accord with the absolute energy scale.

The determination of the mass for the Υ''' is more complicated since this state already lies above the $B\bar{B}$ threshold. At present the exact resonance shape and the underlying continuum level are unknown. For simplicity, the mass quoted by CUSB was obtained by fitting a radiatively corrected gaussian above continuum, assuming no level change [PAC 83].

The leptonic widths can be obtained from the area under the resonances in the hadronic cross-section. To show this consider the process $e^+e^- \rightarrow V \rightarrow \text{channel } i$. The contribution to the resonance cross-section from such a reaction is given by the Breit Wigner formula [BW 52]:

$$\sigma_i := \sigma(e^+e^- \rightarrow V \rightarrow i) = \frac{3\pi}{M_V^2} \frac{\Gamma_{ee}\Gamma_i}{(W-M_V)^2 + \Gamma_{\text{tot}}^2/4} \quad (2.1)$$

where $W=\sqrt{s}$ is the CM energy, Γ_{tot} the total width, Γ_{ee} the partial leptonic width for $V \rightarrow e^+e^-$ and Γ_i the partial width for $V \rightarrow i$. Summing eq. (2.1) over all channels with hadrons in the final state and integrating over the resonance region one gets:

$$S_{\text{had}} := \int dW \sigma_{\text{had}} = \frac{6\pi^2}{M_V^2} \frac{\Gamma_{ee} \Gamma_{\text{had}}}{\Gamma_{\text{tot}}} \quad (2.2)$$

The area S_{had} under the resonance is independent of the observed resonance shape. If we define the leptonic branching ratio:

$$B_{\mu\mu}(V) := \Gamma(V \rightarrow \mu^+\mu^-) / \Gamma(V \rightarrow \text{all}) \quad (2.3)$$

and assume lepton universality, i.e. $B_{\mu\mu} = B_{ee} = B_{\tau\tau}$ we can substitute $\Gamma_{\text{had}}/\Gamma_{\text{tot}}$ by $(1-3 \cdot B_{\mu\mu})$ as shown in appendix A. This finally leads to:

Table 2.1 Measured masses of 3S_1 -states in the T -system

Masses [MeV]

Exp.	T	T'	T''	T'''	[ref.]
LENA	$9461.6 \pm 0.5 \pm 10$	$10013.6 \pm 1.2 \pm 10$	-----	-----	[Ni 81]
DASPII	$9463.1 \pm 0.8 \pm 10$	$10016.8 \pm 1.5 \pm 10$	-----	-----	[A1 80]
ARGUS, CB	-----	* $10023.1 \pm 0.4 \pm .5$	-----	-----	[Ba 83]
CUSB	* $9459.9 \pm 0.1 \pm .1$	$10023.6 \pm 0.6 \pm .3$	$10350.2 \pm 0.7 \pm 3$	$10578.2 \pm 3 \pm 5$	[Mc 83] [PAC83]
CLEO	-----	$10021.4 \pm 0.6 \pm 3$	$10352.3 \pm 0.7 \pm 3$	$10575.2 \pm 1.1 \pm 5$	[P1 83]
VEPP-4	* 9460.6 ± 0.4	* 10023.8 ± 0.5	* 10355.5 ± 0.5	-----	[Si 83]
Average	9460.0 ± 0.1	10023.5 ± 0.4	10355.3 ± 0.5	10576.4 ± 3.8	

The asterix indicates a precision measurement with the spin depolarization method.
The second error shows the systematic uncertainties.

Table 2.2 Measured leptonic widths for the T -resonances

Γ_{ee} [keV]

Exp.	T	T'	T''	T'''	[ref.]
PLUTO	$1.33 \pm .14$	-----	-----	-----	[Be 79]
DASP II	$1.35 \pm .11 \pm .22$	$.61 \pm .11 \pm .11$	-----	-----	[A1 80]
LENA	$1.13 \pm .09 \pm .08$	$.53 \pm .07 \pm .06$	-----	-----	[Ni 82]
CLEO	$1.30 \pm .05 \pm .08$	$.52 \pm .03 \pm .04$	$.42 \pm .04 \pm .03$	$.32 \pm .03 \pm .05$	[P1 83]
CUSB	$1.15 \pm .05 \pm .1$	$.56 \pm .03 \pm .05$	$.39 \pm .02 \pm .03$	$.21 \pm .05 \pm .04$	[Yo 83]
Average	$1.24 \pm .05$	$.54 \pm .03$	$.40 \pm .03$	$.27 \pm .04$	

The second error shows the systematic uncertainties.

Table 2.3 Visible hadronic cross section for the Υ resonances

	$\sigma_{\text{cont}}^{\text{had}}$ [nb]	$\sigma_{\text{res}}^{\text{had}}$ [nb]	$\sigma_{\text{tot}}^{\text{had}}$ [nb]
Υ	$3.2 \pm .3$	$16.2 \pm .2$	$19.4 \pm .4$
Υ'	$2.74 \pm .07$	$5.9 \pm .1$	$8.6 \pm .1$
Υ''	$2.67 \pm .03$	$3.49 \pm .07$	$6.11 \pm .08$
Υ'''	$3.0 \pm .1^{+)}$	$0.9 \pm .1$	$3.9 \pm .1$

$\sigma_{\text{cont}}^{\text{had}}$ refers to the hadronic continuum contribution, $\sigma_{\text{res}}^{\text{had}}$ to the resonance cross section, and $\sigma_{\text{tot}}^{\text{had}}$ to the total hadronic cross section.

All data are CUSB measurements (from summer 1980 to summer 1983).

$^{+)}$ Continuum above the Υ''' .

Table 2.4 Measured dilepton branching ratios

Exp.	$B_{\mu\mu}$ [%]			[ref.]
	Υ	Υ'	Υ''	
PLUTO	5.1 ± 3.0	--	--	[Be 79]
DASP II	3.1 ± 1.6	--	--	[Al 80]
LENA	$3.8 \pm 1.5 \pm .2$	< 3.8	--	[Ni 82]
ARGUS	$2.8 \pm 0.4 \pm .3$	--	--	[Al 83]
CLEO	$2.7 \pm 0.3 \pm .3$	$1.9 \pm 1.3 \pm .5$	$3.3 \pm 1.3 \pm .7$	[As 83]
	$3.4 \pm 0.5 \pm .5^{+)}$	--	--	[Gi 83]
CUSB	$2.7 \pm 0.3 \pm .3$	$1.9 \pm 0.3 \pm .5$	--	[Ho 83]
Average	2.9 ± 0.2	1.9 ± 0.6	3.3 ± 1.5	

The second error indicates the systematic uncertainties.

$^{+)}$ This measurement is obtained from $\Upsilon \rightarrow \tau^+ \tau^-$.

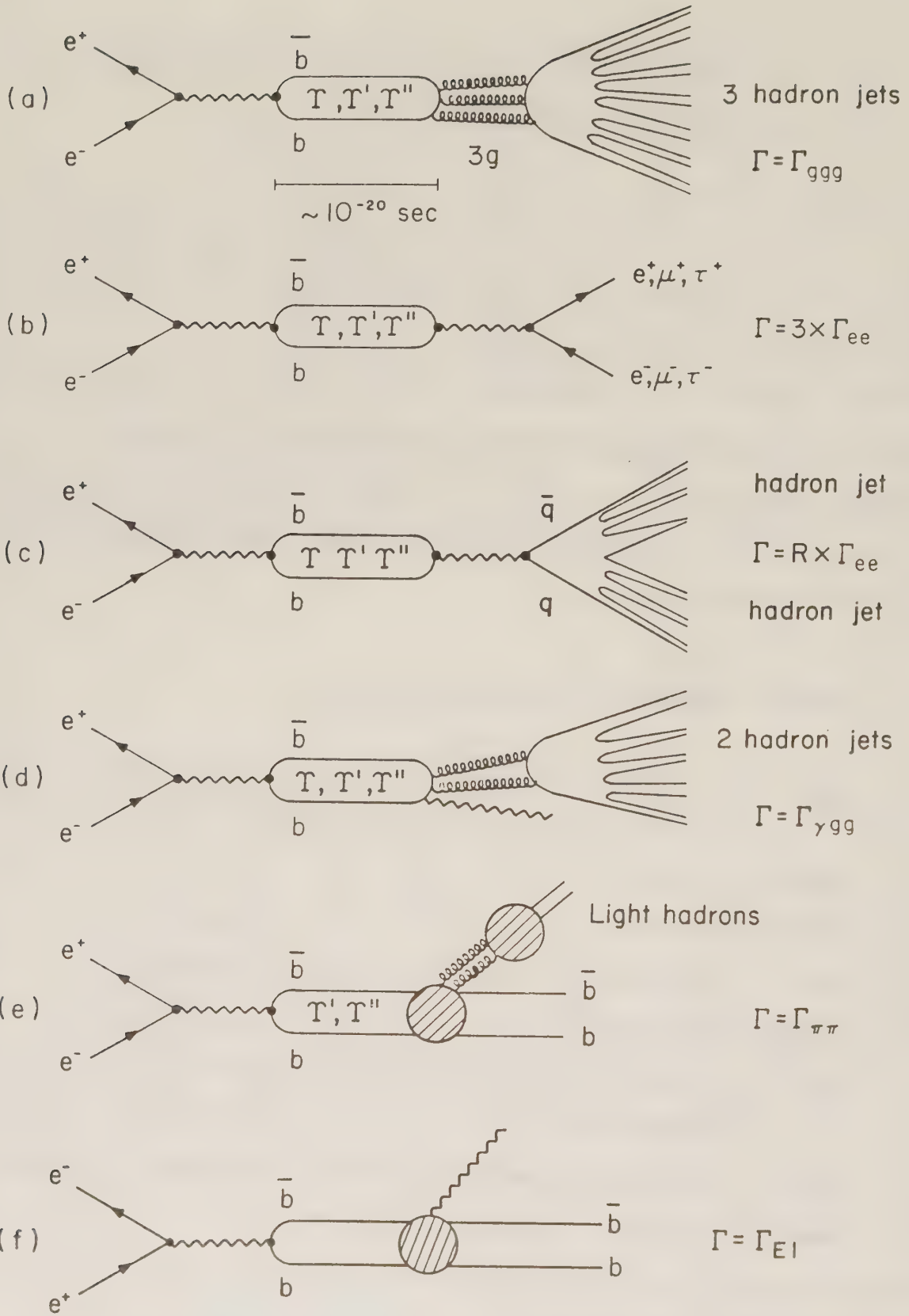


Fig. 2.3 Lowest order diagrams for decay modes of the narrow T states:
a) 3 gluon annihilation, b) annihilation into lepton pairs,
c) annihilation into $q\bar{q}$ jets, d) annihilation into a photon plus
two gluon jets, e) hadronic transition, f) photon transition

$$\Gamma_{ee}(V) = \frac{M_V^2}{6\pi^2} \cdot \frac{S_{had}(V)}{1-3 \cdot B_{\mu\mu}(V)} \quad (2.4)$$

Table 2.2 shows the leptonic widths for the $\mathbf{T}$ states measured by different experiments. The visible hadronic cross sections measured with the CUSB detector are given in table 2.3.

To measure $B_{\mu\mu}$ one has to measure precisely the $\mu^+\mu^-$ yield on and off resonance. At CESR the $\mu^+\mu^-$ yield on the $\mathbf{T}$ resonance is expected to increase by 60% compared to the continuum nearby, which has a cross section $\sigma_{con}(e^+e^- \rightarrow \mu^+\mu^-) \simeq .98$ nb. The measurements for $B_{\mu\mu}$ are listed in table 2.4. Knowing $B_{\mu\mu}$ one can determine the total natural width of the narrow $\mathbf{T}$ states according to :

$$\Gamma_{tot} = \Gamma_{ee}/B_{\mu\mu} \quad (2.5a)$$

From tables 2.2 and 2.4 one obtains for the $\mathbf{T}$ a total width of $\Gamma_{tot}(\mathbf{T}) = (42.8 \pm 3.4)$ keV. However, since for the radially excited states the measurements of $B_{\mu\mu}$ have relatively large errors, one can get a better determination of $\Gamma_{tot}(n)$ according to eq. (A.4) in appendix A:

$$\Gamma_{tot}(n) = \Gamma_{ee}(n) / [B_{\mu\mu}(\mathbf{T})(1-B_{\pi\pi}(n)-B_{E1}(n))] \quad (2.5b)$$

where $B_{\pi\pi}(n)$ denotes the branching ratios for $\pi\pi$ transitions from the n^3S_1 -state to lower 3S_1 states and B_{E1} the branching ratios for photon transitions from the n^3S_1 -state to the nearest 3P -states. Total widths derived from eq. (2.5b) for the $\mathbf{T}'$ and $\mathbf{T}''$ are shown in table A.1 in appendix A.

The individual decay modes contributing to Γ_{tot} are entirely different for the narrow $\mathbf{T}$ resonances and the $\mathbf{T}''$ as shown in fig. 2.3 and fig. 2.4, respectively. The narrow resonances decay dominantly into 3 gluons which subsequently fragment into 3 hadron jets (fig. 2.3a). The 3 gluon decay^{+) is a suppressed decay mode according to the Okubo-Zweig-Iizuka (OZI) rule [OZI 64], thus accounting for the long lifetime of $\sim 10^{-20}$ sec which leads to very sharp resonances in the cross section. Another large decay mode -- at the order of 20% for the $\mathbf{T}$ -- is the annihilation into a}

^{+) This is the lowest order process allowed by QCD, since the one gluon decay is forbidden by color conservation and the two gluon decay violates angular momentum and C-parity conservation.}

virtual photon creating a lepton-antilepton or lighter quark-antiquark pair (vacuum polarizations), where the quarks fragment into 2 hadron jets (fig. 2.3b,c). The interesting mode $\gamma g g$ resulting in an energetic photon plus 2 gluon jets (fig. 2.3d) contributes only at the 3% level. For the higher radially excited states Υ' and Υ'' there are additional large contributions from transitions into other bound states (figs. 2.3e,f), to a lower 3S -state with the emission of two pions (30% for Υ' , 10% for Υ'') or to the nearest 3P_J states with the emission of a photon (15% for Υ' , 35% for Υ'').

Resonances above the $B\bar{B}$ threshold ($M > 10.5$ GeV) decay after only 10^{-23} sec almost entirely into B meson pairs (fig. 2.4). This is a decay mode allowed by the OZI rule. Therefore the lifetime is ~ 1000 times shorter than that of the bound states leading to a broad resonance in the cross section. For example for the Υ'' the total width is $\Gamma_{\text{tot}} = (20 \pm 3)$ MeV [Ri 83, Yo 83].

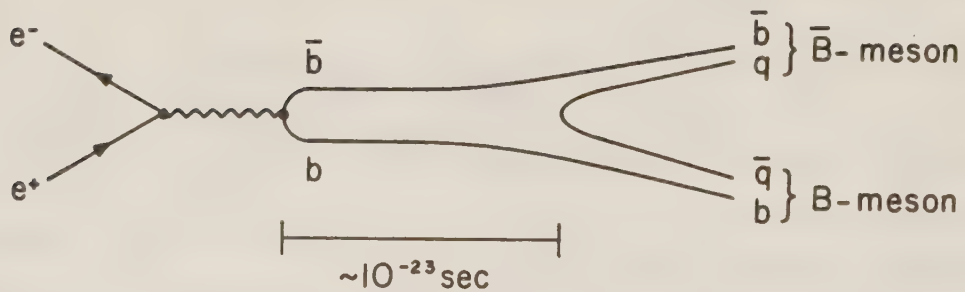


Fig. 2.4 Lowest order diagram for Υ''' decays.

II.2 Potential Models

In potential models the Schrödinger equation is solved for the $q\bar{q}$ system with a non-relativistic effective central potential $V_{\text{NR}}(r)$ similar to the case of positronium. This leads to the Hamiltonian:

$$H_0 = 2m_q + \vec{p}^2/m_q + V_{\text{NR}}(r) \quad (2.6)$$

The same potential can be used to describe both the $c\bar{c}$ and $b\bar{b}$ systems, indicating that the potential is flavor independent⁺⁾ . Since the discovery of the ψ and the T systems the number of different models attempting to describe the experimental results has grown abundantly. In the following section some of the basic models are discussed in more detail.

II.2.1 Non Relativistic Potentials

Essentially there are two different approaches for the construction of a potential: In the first approach an empirical potential is chosen, using little or no theoretical input. One such ad hoc potential is the simple power law potential suggested by Martin [Ma 81]:

$$V_{NR}(r) = A + Br^v, \text{ with } v=.1 \quad (2.7)$$

The parameters A, B, and v, as well as the quark masses m_b , m_c and m_s , are determined in a global fit using data from the ϕ , ψ and T systems. In particular the $M_{T^0} - M_{T^+}$ mass splitting is reproduced correctly.

Another example is the logarithmic potential devised by Quigg and Rosner [QR 77]:

$$V_{NR}(r) = C \ln(r/r_0) \quad (2.8)$$

where C and r_0 are free parameters. The motivation for such a potential originated from the observation of nearly equal mass differences $M_{\psi^0} - M_{\psi^+} = 588$ MeV and $M_{T^0} - M_{T^+} = 563$ MeV. In a logarithmic potential the mass splitting is independent of the quark mass and hence should be equal in both the ψ and T systems. Sterling, for example, had used this potential to make one of the earliest predictions for the photon spectra from electromagnetic transitions in the T -system [St 78]. Another method applied by Quigg and Rosner, called the inverse scattering method, uses all information of the measured spectra as input to construct numerically an approximate form of the static $q\bar{q}$ potential [QR 79, 81]

More interesting, however, is the second approach of constructing potentials inspired by QCD. According to QCD the strength of the coupling

⁺⁾ However the predictions are expected to be better for the more massive bottomonium system. For example the electric dipole transitions rates in charmonium were a factor ~ 3 off using the non-relativistic description (see table 5.7).

constant depends on the distance between the quarks (running coupling constant). At short distance ($r \rightarrow 0$) the coupling becomes very small, i.e. the quarks essentially move freely. This is referred to as asymptotic freedom of QCD. At large distances ($r \rightarrow \infty$), however, the coupling grows resulting in a permanent confinement of quarks.

The QCD inspired potentials can be written in the simple general form:

$$V_{NR}(r) = V_{AF}(r) + V_C(r) = \frac{-K}{r} + \lambda r \quad (2.9)$$

V_{AF} describes the short distance part ($r < 0.1$ fm) of the quark-antiquark interaction. The Coulombic form is motivated by the one gluon exchange at small distance. The parameter K is related to the strong coupling constant by $K = (4/3)\alpha_s(r)$. $V_C(r)$ represents the confining long range part of the potential ($r > 1.0$ fm). The linear form is suggested by the string model or lattice gauge theories, since perturbative QCD does not apply. The parameter λ is the string tension. However, for the intermediate region between 0.1 fm and 1.0 fm, i.e. the region where the Ψ and T states are located, the exact form of the potential is not known. At present no theory of bound states in QCD exists. Even in the nonrelativistic limit the quark-antiquark potential cannot be derived from first principles.

The first QCD inspired potential has been suggested by the Cornell group using the simple form of eq. (2.9) [Ei 78, 80]. For the Ψ system the parameters K and λ are fixed by the measured level spacings $M_{\Psi}, -M_{\Psi}$ and $M_{\chi_c} - M_{\Psi}$ (M_{χ_c} : center-of-gravity of 3P $c\bar{c}$ states) to be $K = .52$ and $\lambda = .925$ GeV/fm, producing a nearly logarithmic potential between 0.1 and 1.0 fm. The c quark mass is parametrized by the relative mean square velocity of the $c\bar{c}$ pair within the Ψ state $\beta_{\Psi}^2 = \langle v^2/c^2 \rangle_{\Psi}$. For calculations a small value of $\beta_{\Psi}^2 = .2$ is chosen. For the T system the effective Coulomb coupling constant K has been adjusted to the $M_{T}, -M_{T}$ level spacing, yielding $K = .48$. The b quark mass is eliminated by the measured T mass.

A successful modification of this potential is the hybrid potential suggested by Bhanot and Rudaz [BR 78]:

$$V_{NR}(r) = \begin{cases} -\frac{4}{3} \frac{\alpha_s}{r} & r < r_1 \\ c \cdot \ln(r/r_0) & r_1 < r < r_2 \\ \lambda \cdot r & r_2 < r \end{cases} \quad (2.10)$$

The six parameters reduce to two by requiring the potential and its first derivative to be continuous at boundaries leaving, for instance, α_s^+ and λ . The constants α_s and λ as well as the quark masses m_c and m_b are fitted using the experimental input from the mass difference $M_{\psi} - M_{\psi'}$, the leptonic widths $\Gamma_{ee}(\psi)$, $\Gamma_{ee}(\psi')$, and the mass M_{η} . A variation of potential (2.10), discussed by Krasemann and Ono, considers explicitly asymptotic freedom for α_s [KO 79].

The potential model most explicitly based on QCD has been proposed by Richardson [Rn 79]. In momentum space the potential is defined by:

$$V(q^2) = \frac{-16\pi}{3} \frac{1}{q^2} \frac{1}{b_0 \ln(1 + q^2/\Lambda^2)} \quad (2.11)$$

where $b_0 = (11 - 2/3N_f)$ and N_f is the number of quark flavors. The only free parameter Λ is fixed by the $M_{\psi} - M_{\psi'}$ mass splitting. This potential is asymptotically free for $b_0 > 0$, and satisfies the confinement condition as can be seen from the asymptotic limits:

$$\lim_{q^2 \gg \Lambda^2} V(q^2) = \frac{-16\pi}{3} \frac{\alpha_s(q^2)}{q^2} = \frac{-16\pi}{3} \frac{1}{q^2} \frac{1}{b_0 \ln(q^2/\Lambda^2)} \quad (2.12a)$$

$$\lim_{q^2 \ll \Lambda^2} V(q^2) = \frac{C}{(q^2)^2} \quad (2.12b)$$

with $C = (16\pi/3)\Lambda^2/b_0$. The first equation represents the Coulomb potential in momentum space with $\alpha_s(q^2)$ obtained from the one-loop QCD expansion, the second the Fourier transformation of a linear potential.

Buchmüller and Tye (BT model) have extended the Richardson potential to include higher order QCD contributions in α_s [BT 81]. The potential is expressed in the general form in momentum space by:

$$V(q^2) = \frac{-16\pi}{3} \frac{\alpha_s(q^2)}{q^2} \quad (2.13)$$

The asymptotic limits of $\alpha_s(q^2)$ are given by:

⁺) α_s is treated as a constant like K in the Cornell potential.

$$\lim_{q^2 \rightarrow \infty} a_s(q^2) \propto \frac{1}{b_0 \ln(q^2/\Lambda^2)} - \frac{b_1}{b_0^3} \cdot \frac{\ln \ln(q^2/\Lambda^2)}{\ln^2(q^2/\Lambda^2)} \quad (2.14a)$$

$$\lim_{q^2 \rightarrow 0} a_s(q^2) \propto \frac{K}{q^2} \quad (2.14b)$$

where b_0 is the same as before and $b_1 = 102 - (38/3) \cdot N_f^{+})$. Eq (2.14a) is obtained from the two-loop QCD perturbation expansion of the running coupling constant for large q^2 , whereas eq. (2.14b) results as usual from the requirement that the Fourier transformation of eq. (2.13) is linear in r for $r \rightarrow \infty$. Interpolating the running coupling constant between these two limits with the requirement that the resulting potential has to provide a description of both the Ψ and T systems the authors have derived the following function:

$$a_s(q^2) = \frac{1}{b_0 \ln[1 + \eta(q^2) \cdot q^2/\Lambda^2]} \quad (2.15)$$

where

$$\eta(q^2) = \left[\frac{24}{b_0} \right]^{b_1/b_0^2} \cdot \exp \left[\frac{b_1}{b_0^2} (\gamma_E + E_1(24\rho_0(q^2))) \right] \quad (2.16a)$$

and

$$\rho_0 = 1/[b_0 \ln(1+q^2/\Lambda^2)] \quad (2.16b)$$

In eq. (2.16a) $\gamma_E = .5772$ is the Euler constant and $E_1(x)$ the exponential integral. The factor 24 is empirically adjusted and is supposed to take care of higher orders. In the limit $b_1=0$ it follows that $\eta(q^2)=1$, in which case eq. (2.13) becomes identical to the Richardson potential.

In this model the arbitrary parameter Λ is related to the QCD scale parameter $\Lambda_{\overline{MS}}^{++})$ by :

$$\ln(\Lambda/\Lambda_{\overline{MS}}) = \frac{1}{2b_0} \left(\frac{31}{3} - \frac{10}{9} N_f \right) \quad (2.17)$$

^{+) b_0 and b_1 are calculated for QCD using SU(3).}

and K to the Regge slope $\alpha' = 3/(16\pi^2 K)$. Since this model also has only one free parameter, the following relationship between α' and $\Lambda_{\overline{MS}}$ holds:

$$\ln(\alpha' \Lambda_{\overline{MS}}^2) = -\ln\left[\frac{16\pi^2}{3}\right] + \ln b_0 + \frac{b_1}{b_0^2} [\gamma_E + \ln \frac{24}{b_0}] - \frac{1}{b_0} \left[\frac{31}{3} - \frac{10}{9} N_f\right] \quad (2.18)$$

For four quark flavors one gets $\alpha' \Lambda_{\overline{MS}}^2 = 0.26$. Using the slope $\alpha' = 1 \text{ GeV}^{-2}$, which is determined in light hadron spectroscopy, yields $\Lambda_{\overline{MS}} = 500 \text{ MeV}$. Thus the potential (2.13) is completely determined. From the Fourier transformation of eq. (2.13) the non-relativistic potential $V_{NR}(r)$ is obtained. The quark masses m_c and m_b are fixed by using the ground state masses M_ψ and M_T as input. However, due to the weak dependence on $\Lambda_{\overline{MS}}$, acceptable fits to data can be made with any value of $\Lambda_{\overline{MS}}$ between 100 MeV and 500 MeV.

Fig. 2.5 displays five of the potentials discussed above as a function of r , where models a, c, d and e have been shifted to coincide with model b at $r=0.5 \text{ fm}$. The error bars indicate the uncertainty in the absolute, r -independent normalization. Also shown are the mean-square radii of the ψ and T states. All potentials are nearly identical in the range of $0.1 \text{ fm} < r < 1.0 \text{ fm}$, the region where the ψ and T states are located. For $r < 0.1 \text{ fm}$ the five potentials differ substantially. Unfortunately, the T is not heavy enough to probe the short range potential. However, the toponium system will provide such tests. For a mass $m_t = 30 \text{ GeV}$ one expects $\langle r^2 \rangle^{1/2} \approx 0.08 \text{ fm}$ [BT 81]. For $r > 1.0 \text{ fm}$ the potential must be increasing but the exact form is hard to determine. For example at larger $q\bar{q}$ separations effects from light quark pair creation -- leading to the formation of meson pairs -- become more significant [Ei 80,83].

Other more complex and sophisticated potential models are given in the literature. But essentially, they are based on the models discussed above. More recent calculations include in addition relativistic corrections (see II.2.3). Besides potential models there exist calculations from QCD sum rules [Vo 80, Bn 81] and Bag models [Ba 81] which predict $q\bar{q}$ energy levels and decay rates.

++) α_s and Λ depend on the renormalization scheme used. For definition and discussion of the modified minimal subtraction ($\overline{MS}$) scheme see [Bn 78]. The relation between $\Lambda_{\overline{MS}}$ (minimal subtraction) and $\Lambda_{\overline{MS}}$ and Λ_{mom} (momentum space) is $\Lambda_{\overline{MS}} = 0.377 \Lambda_{\overline{MS}}, \Lambda_{\text{mom}} = 2.16 \Lambda_{\overline{MS}}$ [CG 79].

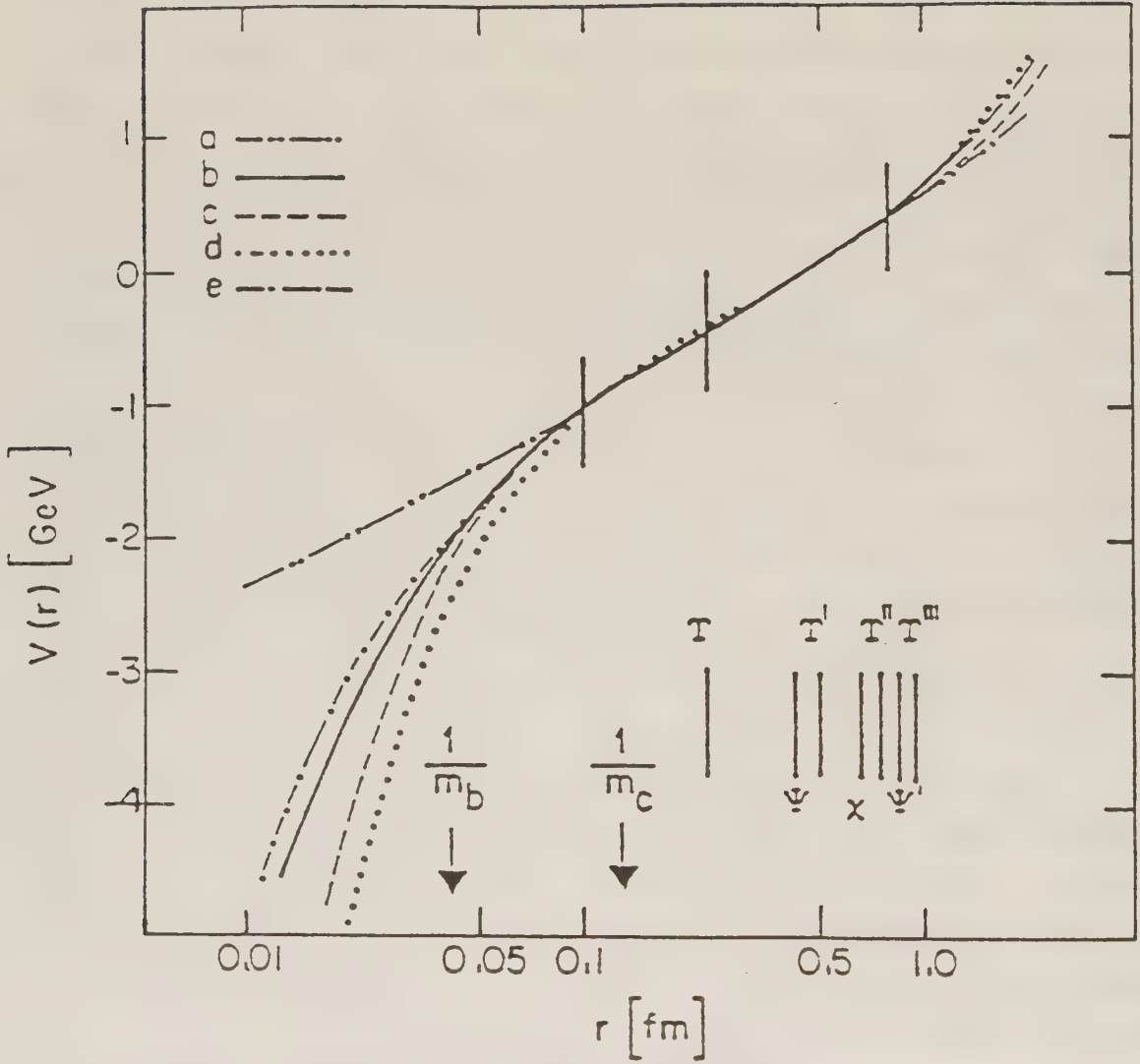


Fig. 2.5 Quark-antiquark potential for different non-relativistic potential models: a) Martin, b) Buchmüller-Tye, c) Bhanot-Rudaz, d) Eichten et al., and e) Krasemann-Ono. The potentials a, c, d, and e have been shifted to coincide with b at $r=0.5$ fm. The 'error bars' indicate the uncertainty in absolute, r -independent normalization. States of the Ψ and T families are displayed at their mean-square radii.

II.2.2 Model Predictions

With non-relativistic potentials one can predict energy eigenvalues and wave functions for heavy $q\bar{q}$ states. However, since no spin dependent forces are considered only center-of-gravities (cog's) can be determined for different orbitally excited states.

For example, in the $b\bar{b}$ system the 1^3P_{cog} is expected to be ~ 120 MeV below the T' , the 2^3P_{cog} ~ 100 MeV below the T'' . Some predictions for masses of 3S_1 states in the $b\bar{b}$ system are listed in table 2.5. Input values are marked by an asterisk. Usually, the T mass is taken as input. For the narrow resonances the agreement between predicted and measured masses is remarkable. Most of the models predict the observed mass differences $M_{T'} - M_T = (563.5 \pm 4)$ MeV and $M_{T''} - M_{T'} = (895.3 \pm 5)$ MeV correctly within $\sim 1\%$. For the 4^3S_1 state, however, the mass predictions are less accurate. Except for the MB model [MB 82] all predictions give too high a mass, ranging between 25 MeV and 120 MeV above the observed T''' mass. However, since the 4^3S_1 state already lies above the $B\bar{B}$ threshold effects due to light quark pair creation are expected to be important. In addition relativistic corrections are expected to become larger with increasing $\langle r^2 \rangle^{1/2}$. For the T''' one finds $\langle v^2/c^2 \rangle \approx 0.1$.

Knowing the wave functions allows one to determine the different decay and transition rates for $q\bar{q}$ bound states. For example the leptonic width Γ_{ee} for the n th T state is given by the first order QCD radiative corrected Van Royen-Weisskopf formula [VW 67, Ba 75]:

$$\Gamma_{ee}(n) = \frac{16\pi\alpha^2 e_b^2}{M_n^2} |\psi_n(0)|^2 [1 - (16/3\pi) \alpha_s(2m_b) + \Delta] \quad (2.19)$$

where M_n is the mass of the n th T -state, α the fine structure constant, e_b the b quark charge, and $\psi_n(0)$ the wave function at the origin. The parameter Δ is an estimate for unknown higher order radiative and relativistic corrections. Some predictions for the leptonic widths are listed in table 2.6. However, theorists prefer to quote the ratios $\Gamma_{ee}(n^3S_1)/\Gamma_{ee}(1^3S_1)$, which cause unknown higher order QCD and relativistic corrections to cancel. Except for the Kang model all predicted ratios are in good agreement with the measurements. Very impressive are the precise predictions of the empirical power law potential suggested by Martin. Considering the experimental error and the theoretical uncertainties the

Table 2.5 Predicted masses for n^3S_1 -states in the $b\bar{b}$ system.

Masses are in MeV. An asterix indicates an input to the model.

Model	1^3S_1	2^3S_1	3^3S_1	4^3S_1	5^3S_1	[ref]
Bhanot, Rudaz	9460*	10026	10339	10583	-----	[BR 78]
Sterling	9460*	10047	10370	-----	-----	[St 78]
Beavis et al.	9466	10002	10369	10673	-----	[Bs 79]
Richardson	9460*	10015	10346	10607	-----	[Rn 79]
Cornell	9460*	10024	10364	10637	10879	[Ei 80]
Baake et al. A B	9460*	10020*	10365	10678	-----	[Ba 81]
	9460*	10020*	10365	10682	-----	
Buchmüller, Tye	9460*	10020	10350	10620	10850	[BT 81]
Eichten, Feinberg	9460*	10020	10350	10670	-----	[EF 81]
Krasemann	9460*	10029	10364	10605	10835	[Kr 81]
Kuang, Yan	9460*	10020	10360	-----	-----	[KY 81]
Martin	9460	10025	10360	10600	10760	[Ma 81]
Barik, Jena	9460*	10029	10364	10605	-----	[BJ 82]
Gupta, et al.	9460*	10011	10353	-----	-----	[Gu 82]
McClary, Byers	9460*	10020	10355	10574	-----	[MB 82]
Gupta et al.	9462	10013	10355	-----	-----	[Gu 83]
Hagiwara, et al.	9459	10034	10367	-----	-----	[Ha 83]
Kang	9460*	10002	10383	10699	-----	[Ka 83]
Kühn, Ono A B	9460*	10016	10347	-----	-----	[KO 83]
	9460*	10009	10344	-----	-----	
Moxhay, Rosner	9460*	10020*	10350*	10607	-----	[MR 83]
Experiment (average)	9460	10023.5	10355.3	10576	-----	from Table 2.1

Table 2.6 Predicted leptonic width $\Gamma_{ee}(1S)$ and ratios $\Gamma_{ee}(n^3S_1)/\Gamma_{ee}(1^3S_1)$ in the $b\bar{b}$ system.

Model	$\Gamma_{ee}(1S)$ [keV]	$\Gamma_{ee}(2S)/\Gamma_{ee}(1S)$	$\Gamma_{ee}(3S)/\Gamma_{ee}(1S)$	$\Gamma_{ee}(4S)/\Gamma_{ee}(1S)$	[ref]
Bhanot, Rudaz	1.77	0.43	0.29	0.24	[BR 78]
Cornell	$1.25 \pm .16$	0.39	0.27	0.23	[Ei 80]
Voloshin ^{a)}	$1.15 \pm .2$	----	----	----	[Vo 80]
BT	$1.07 \pm .24$	0.44	0.32	0.26	[BT 81]
Krasemann	1.05	0.43	0.31	0.25	[Kr 81]
Martin	----	0.41	0.35	0.27	[Ma 81]
Barik, Jena	----	0.504	0.339	0.258	[BJ 82]
MB	1.38	0.39	0.29	0.24	[MB 82]
Gupta	1.29	0.48	0.36	----	[Gu 83]
Kang	$1.25(.76)^b)$	0.59	0.47	0.42	[Ka 83]
MR	----	0.41	0.29	0.24	[MR 83]
Experiment (average)	1.24 ± 0.05	0.44 ± 0.03	0.34 ± 0.03	0.22 ± 0.03	from table 2.2

The theoretical error results from relativistic effects and higher order QCD corrections.

a) Prediction from QCD sum rules.

b) First value is without QCD corrections, the second with first order QCD corrections.

predictions for $\Gamma_{ee}(\Upsilon)$ are also consistent with the measurements. For example in the BT model the predicted width of $\Gamma_{ee}(\Upsilon)=1.07\pm.24$ is in good agreement with the measured world average of $\Gamma_{ee}(\Upsilon)=1.24\pm.05$.

The 3 gluon decay rate Γ_{ggg} with first order QCD corrections is given by [Ap 75, Ba 76]:

$$\Gamma_{ggg}(n) = \Gamma_{ggg}^0(n) \cdot (1 + 3.8a_s/\pi) \quad (2.20)$$

with:

$$\Gamma_{ggg}^0(n) = \frac{40}{81} \alpha_s^3(2m_b) \cdot (\pi^2 - 9) \frac{|\psi_n(0)|^2}{m_b^2} \quad (2.21)$$

Γ_{ggg}^0 is identical to the 3 photon decay rate in positronium apart from an SU(3) color factor.

A further prediction can be made on the number of $q\bar{q}$ bound 3S_1 -states since the principle quantum number n is obtained from the Bohr-Sommerfeld quantization.

$$n = \frac{1}{4} + \text{cons} \cdot \sqrt{m_q} \quad (2.22)$$

Fixing the constant from charmonium ($n=2$) one expects $n=3$ for bottomonium and $n \geq 8$ for toponium if $m_t \geq 30$ GeV [KK 79].

II.2.3 Fine and Hyperfine Splitting

To calculate the fine and hyperfine splittings one has to consider spin-dependent interactions similar as in atomic physics. This leads to the spin-dependent Breit-Fermi Hamiltonian, which is obtained from a nonrelativistic reduction of the Dirac equation and involves the spin-orbit, spin-spin and tensor interactions. However, an additional model dependent assumption is needed to specify the spin-dependent interaction Hamiltonian explicitly, since no derivation in QCD from first principles exists so far. We follow the arguments of Buchmüller [Bu 82], resulting from the flux tube picture of electric confinement. The flux tube model suggests that at short distances the quark-antiquark interaction is dominated by the one gluon exchange, whereas at large distances the fields in the flux tube at rest are purely electric. Therefore no contribution from the long range potential is expected for the spin-spin and tensor forces. In a rotating $q\bar{q}$ system the magnetic fields in the co-moving rest frame of the quark and antiquark will

be zero. This leaves only a term from the long range potential in the spin orbit interaction, which is due to the Thomas precession.

Identifying the short range potential with a vector potential $V_V = -(4/3)a_s/r$ and the long range potential with a scalar potential $V_S = \lambda r$ the spin dependent terms in the Breit-Fermi Hamiltonian can be written as:

$$H_{LS} = \frac{1}{2m^2} \vec{L} \cdot \vec{S} \left[3 \frac{d}{dr} V_V - \frac{d}{dr} V_S \right] / r \quad (2.23)$$

$$H_T = -\frac{1}{6m^2} [3(\vec{S} \cdot \hat{r})(\vec{S} \cdot \hat{r}) - S^2] \left[\frac{1}{r} \frac{d}{dr} V_V - \frac{d^2}{dr^2} V_V \right] \quad (2.24)$$

$$H_{SS} = \frac{2\vec{S}^2 - 3}{6m^2} \left[\frac{d^2}{dr^2} V_V + \frac{2}{r} \frac{d}{dr} V_V \right] \quad (2.25)$$

where m is the quark mass, $\vec{S} = \vec{s}_1 + \vec{s}_2$ is the total spin of the $q\bar{q}$ system, $\vec{L}$ its orbital angular momentum and $\hat{r}$ a unit position vector. However, there are other models discussed in the literature with different assumptions on V_S and V_V [EF 81, MB 82, MR 83]. For example the Eichten-Feinberg and Moxhay-Rosner models assume no scalar potential. Instead the vector potential consists of the one gluon exchange at short distances and a confining term which transforms under Lorentz transformations like the fourth component of a four-vector. The consequence is that the long range potential has contributions in all three interactions. However, measurements of the fine and hyperfine splittings will test these assumptions.

As in atomic physics the spin-orbit interaction is understood as the $\vec{B}$ -field caused by the orbital current (proportional to $\vec{L}$) exerting a torque on the spin magnetic moment (proportional to $\vec{s}_i$) which results in a level shift $\Delta E = -\vec{\mu} \cdot \vec{B} \sim \vec{L} \cdot \vec{S}$. Levels with the same orbital angular momentum $\vec{L}$ but different total angular momentum $\vec{J} = \vec{L} + \vec{S}$ are split according to:

$$\vec{L} \cdot \vec{S} = L, -1, -(L+1) \quad \text{for } J = L+1, L, L-1 \quad (2.26)$$

where L represents the orbital angular momentum quantum number.

The tensor force is understood as if the quark-antiquark system is interacting in the manner of two bar magnets. This force mixes states of the same J but different L (S- and D-states, for example) and introduces a splitting among substates of the same L, which is quantitatively different from the spin-orbit splitting. Defining $T:=2[3(\vec{S} \cdot \hat{r})(\vec{S} \cdot \hat{r})-\vec{S}^2]$ one finds the splittings:

$$T = -2L/(2L+3), \quad 2, \quad -2(L+1)/(2L-1) \quad \text{for } J= L+1, L, L-1 \quad (2.27)$$

The tensor and spin-orbit interactions are responsible for the fine splitting. Defining the expectation values a and b for the spin-orbit and tensor terms:

$$a:= \frac{1}{2m^2} \left\langle 3\frac{V'_V}{r} - \frac{V'_S}{r} \right\rangle \quad (2.28)$$

$$b:= \frac{1}{12m^2} \left\langle \frac{V'_V}{r} - V'_V \right\rangle \quad (2.29)$$

the masses of the 3P states, for example, can be parametrized by:

$$M(^3P_2) = M_0 + a - (2/5)b \quad (2.30a)$$

$$M(^3P_1) = M_0 - a + 2b \quad (2.30b)$$

$$M(^3P_0) = M_0 - 2a - 4b \quad (2.30c)$$

where M_0 is the cog of the 3P -state, calculated in non-relativistic potential models. The expected splittings $M(^3P_2)-M(^3P_1)$ and $M(^3P_1)-M(^3P_0)$ range from 10-20 MeV (10-20 MeV) and 20-50 MeV (15-30 MeV) for the $1^3P(2^3P)$ states.

The spin-spin interactions cause a splitting of levels with the same L according to whether the quark spins are parallel ($S=1$) or antiparallel ($S=0$). This is similar as in atoms and is known as hyperfine splitting. The spin factor $\vec{s}_1 \cdot \vec{s}_2 = (\vec{S}^2/2 - 3/4)$ in eq (2.25) is $-3/4$ for $S=0$ and $+1/4$ for $S=1$. Using the Coulomb potential $-k/r$ for V_V one determines a hyperfine splitting of:

$$\Delta E_{\text{HFS}} = \frac{3}{2m^2} \vec{s}_1 \cdot \vec{s}_2 \times 4\pi |\psi(0)|^2 \quad (2.31)$$

$\Psi(0)$ is the wave function at the origin, and is only non-zero for S-states. Thus for a pure Coulomb potential there is no splitting between singlet and triplet states for $L > 0$. However, the short range quark-antiquark potential is not a pure Coulomb potential. Therefore also for $L \neq 0$ a small splitting of a few MeV between singlet and triplet states is expected. For example, if we use a power law potential $A + Br^v$ for $V_v(r)$ we can estimate the splitting between the spin averaged 3P states and the 1P_1 state, yielding [Ro 83]:

$$M_0 - M(^1P_1) = (4/9) \cdot (1+v) a \quad (2.32)$$

where a is the expectation value defined in eq. (2.28) and M_0 the 3P state cog. For $v \approx 0$ and $a \approx 12$ MeV we find a splitting of ~ 5 MeV. On the other hand predictions for the hyperfine splitting between the Υ and η_b range between 14 and 100 MeV. Some predictions for the hyperfine splittings $\Upsilon-\eta_b$ and $1^3P_{\text{cog}}-1^1P_1$ as well as the masses of 1S_0 and 1P_1 states are summarized in table 2.7.

Although non-relativistic potential models involving spin-dependent interactions work very well in predicting the mass spectrum of $b\bar{b}$ states, a more refined calculation also has to include spin-independent relativistic corrections which can be obtained from an expansion of the Dirac equation. Up to order $\langle v^2/c^2 \rangle$ the spin independent terms in the Breit-Fermi Hamiltonian are given by [MB 82]:

$$H_{\text{rel}} = \frac{\vec{p}^4}{4m^3} + \frac{v^2 V_{\text{NR}}(r)}{4m^2} - \frac{\vec{p} \cdot \vec{V}_s \cdot \vec{p}}{m^2} + \vec{p} \cdot \left(1 - \frac{\vec{v} \cdot \vec{v}}{v^2} V_v\right) \cdot \vec{p} / m^2 \quad (2.33)$$

If one sets $V_s=0$, $V_v=-a/r$ and omits the last term, eq. (2.32) would represent the spin independent relativistic corrections for positronium. These relativistic corrections are included in most of the more recent calculations [EF 81, MB 82, MR 83].

II.3 $b\bar{b}$ Spectroscopy

The bottomonium system has a much richer spectrum than the charmonium system, both from hadronic and electromagnetic transitions. However, experimentally the analysis of the $b\bar{b}$ spectrum is much more difficult:

- i) The production cross section of Υ states is smaller due to the smaller quark charge $\sigma \sim e_b^2$ and the smaller CM energy dependence $\sigma \sim 1/s$.
- ii) Electromagnetic transition rates are reduced due to $\Gamma \sim e_b^2$ and a smaller

Table 2.7 Predicted hyperfine splitting and masses of $b\bar{b}$ singlet states. Masses and splittings are in MeV.

Model	$T-\eta_b$	1^1S_0	2^1S_0	3^1S_0	$1^3P_{\text{cog}}-1^1P_1$	1^1P_1	2^1P_1	[ref]
Beavis	22	9438	9988	10359	6	9849	-----	[Bs 79]
Baake	A	86	9374	9984	10335	-	-----	[Ba 81]
	B	81	9379	9985	10334	-	-----	
BT	46	9414	9997	10332	-	-----	-----	[BT 81]
EF	94	9366	9979	10237	4	9924	10231	[EF 81]
Khare	29	9431	-----	-----	13	9858	-----	[Kh 81]
Krasemann	70	9390	-----	-----	-	-----	-----	[Kr 81]
Martin	61	9399	9899	10174	-	-----	-----	[Ma 81]
Barik, Jena	14	9432	10016	10355	7	9855	-----	[BJ 82]
Buchmüller	--	-----	-----	-----	0	9889	10249	[Bu 81]
MB	101	9359	9980	10324	-2	9925	10269	[MB 82]
Gupta	35	9425	9992	10337	2	9898	10256	[Gu 82]
Kang	44	9416	9972	10357	-1	9858	10259	[Ka 83]
MR	57	9403	-----	-----	3	9906	10257	[MR 83]

radius $\langle r_T^2 \rangle^{1/2}$. Magnetic dipole transition rates are further reduced by the large b-quark mass according to eq. (2.38).

- iii) Hadronic transition rates are reduced according to eq. (2.34).
- iv) The predicted fine splitting $\Delta E_{FS} := M(^3P_2) - M(^3P_0)$ is smaller: $\Delta E_{FS}(T) \approx 20-40$ MeV while $\Delta E_{FS}(\psi) \approx 140$ MeV.
- v) The hyperfine splitting of S states is smaller: $\Delta E_{HFS}(T) \approx 50$ MeV while $\Delta E_{HFS}(\psi) \approx 130$ MeV.
- vi) The decay multiplicity is much higher due to higher CM energies both for the T-states and the continuum.

II.3.1 Hadronic Transitions

Many hadronic transitions between bound states are predicted in the $b\bar{b}$ system. Examples are shown in fig. 2.6. These transitions are understood as the emission of soft gluons which subsequently annihilate into light hadrons (fig. 2.7). Since the gluons are soft, perturbative QCD does not work. However, since the wavelength is large compared to the size of the bound states, one can perform a multipole expansion of the gauge field, analogous to electromagnetic transitions [Go 78, KY 81] keeping only the lowest order allowed by selection rules. Since gluons are colored while hadrons in the final state are colorless, at least two gluons have to be emitted to neutralize color. Therefore in the case of vector gluons the lowest order process is a double (colored) electric dipole (E1-E1) transition.

In the $b\bar{b}$ system the most dominant transitions are the $\pi\pi$ transitions between 3S_1 -states (E1-E1 transitions)⁺ with estimated rates for $2^3S_1 \rightarrow \pi\pi 1^3S_1$ to scale like [Ya 80].

$$\Gamma(T' \rightarrow \pi\pi T) / \Gamma(\psi' \rightarrow \pi\pi \psi) \approx (\langle r^2 \rangle_{T'} / \langle r^2 \rangle_{\psi})^2 \approx 1/10 \quad (2.34)$$

The experimental ratio obtained from the measured rates $\Gamma(T' \rightarrow \pi\pi T) = (5.6 \pm 1.9)$ keV [Fo 84] and $\Gamma(\psi' \rightarrow \pi\pi \psi) = (71 \pm 5)$ keV [Ag 82] is 0.079 ± 0.027 which is in good agreement with eq. (2.34). This is actually a significant test of QCD, because in the case of scalar gluons the dominant term in the multipole expansion would be the monopole term, yielding for eq. (2.34) a ratio of the order one [Go 78].

⁺) One pion transitions are forbidden by conservation of isospin. The isospin conservation also implies that the branching ratios for charged pions should be twice as large as for neutral pions.

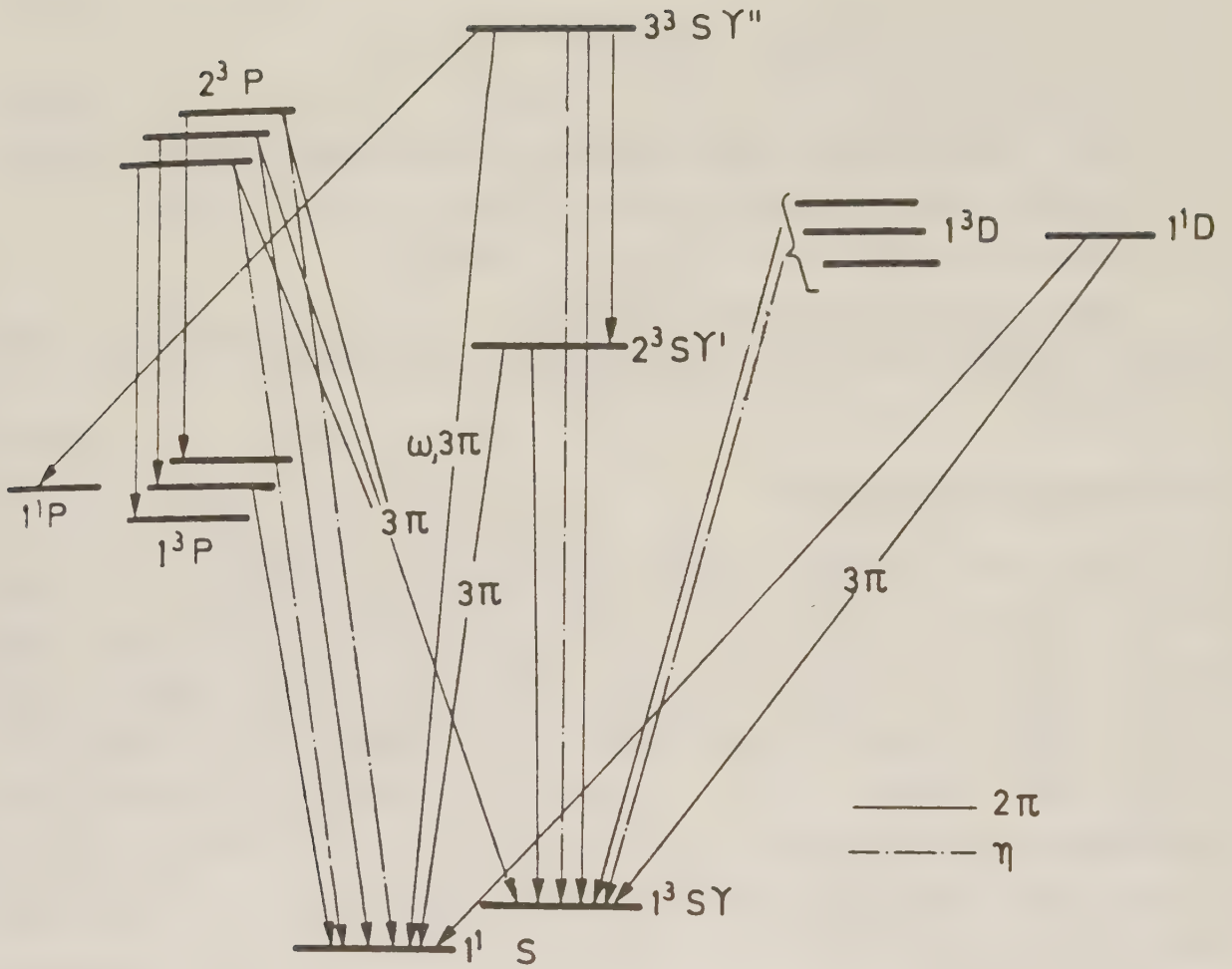


Fig. 2.6 Hadronic transitions in the bottomonium system.

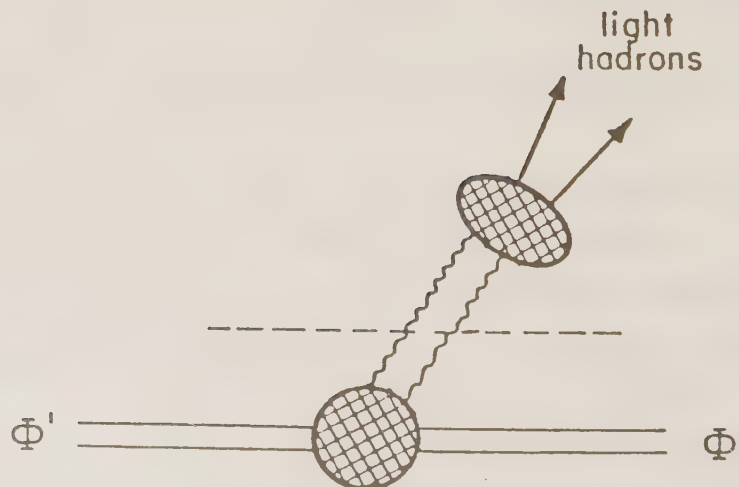


Fig. 2.7 Model of soft gluon emission.

An interesting transition to consider is the $\pi\pi$ transition $\mathbf{T}' \rightarrow \pi\pi^1P_1$, i.e. a (colored) E1-M1 transition with an expected branching ratio of $\sim 1\%$, since the subsequent 1P_1 state decays via an electric dipole transition with a BR of $\sim 40\%$ into the η_b (see Fig. 2.8). By tagging the two pions and searching for a photon of $E_\gamma \sim 450-500$ MeV, one has a promising decay mode for finding the η_b .

Other hadronic transitions are expected to have very small rates, as for example the transition $\mathbf{T}' \rightarrow \eta\mathbf{T}$. Scaling laws derived from the multipole expansion model predict [Ya 80]:

$$\frac{\Gamma(\mathbf{T}' \rightarrow \eta\mathbf{T})}{\Gamma(\Psi' \rightarrow \eta\Psi)} = \left[\frac{m_c}{m_b} \right]^4 \left[\frac{P_\eta(\mathbf{T})}{P_\eta(\Psi)} \right]^3 \approx \frac{1}{300} \quad (2.35)$$

where the phase space ratio (second term) is $\sim 1/4$. For the quark masses typical values of $m_c = 1.8$ GeV and $m_b = 5.2$ GeV have been used. From $\Gamma(\Psi' \rightarrow \eta\Psi) = (6 \pm 1)$ keV [Ag 82] one estimates $\Gamma(\mathbf{T}' \rightarrow \eta\mathbf{T}) \approx 20$ eV.

II.3.2 Electromagnetic Transitions

Electromagnetic transitions provide an extremely important means of searching for $q\bar{q}$ bound states with $J^{PC} \neq 1^{--}$, which cannot be produced directly in e^+e^- collisions. Fig. 2.8 shows examples of electromagnetic transitions in the $b\bar{b}$ system. Electric dipole (E1) transitions are most dominant⁺). The quantum numbers for the orbital angular momentum and total angular momentum of the initial state L_i, J_i and the final state L_f, J_f are related by $L_f = L_i \pm 1$ and $|J_f - 1| \leq J_f \leq J_i + 1$. In addition the parities of initial and final states change. The E1 transition rates for $n^3S_1 \rightarrow \gamma n'^3P_J$ and $n^3P_J \rightarrow \gamma n'^3S_1$ transitions are given by [QR 81]:

$$\Gamma(n^3S_1 \rightarrow \gamma n'^3P_J) = \frac{4}{27} \cdot \alpha e_b^2 k_\gamma^3 \cdot (2J_f + 1) \cdot |\langle f | r | i \rangle|^2 \quad (2.36a)$$

$$\Gamma(n^3P_J \rightarrow \gamma n'^3S_1) = \frac{4}{9} \cdot \alpha e_b^2 k_\gamma^3 \cdot |\langle f | r | i \rangle|^2 \quad (2.36b)$$

where α is the fine structure constant ($\sim 1/137$), e_b the b-quark charge,

⁺) A multipole expansion of the electromagnetic field is justified because the expansion parameter $(kr/2)^2$ is small. For a photon energy of $k = 125$ MeV and a radius of 0.5 fm one finds $(kr/2)^2 \approx .025$.

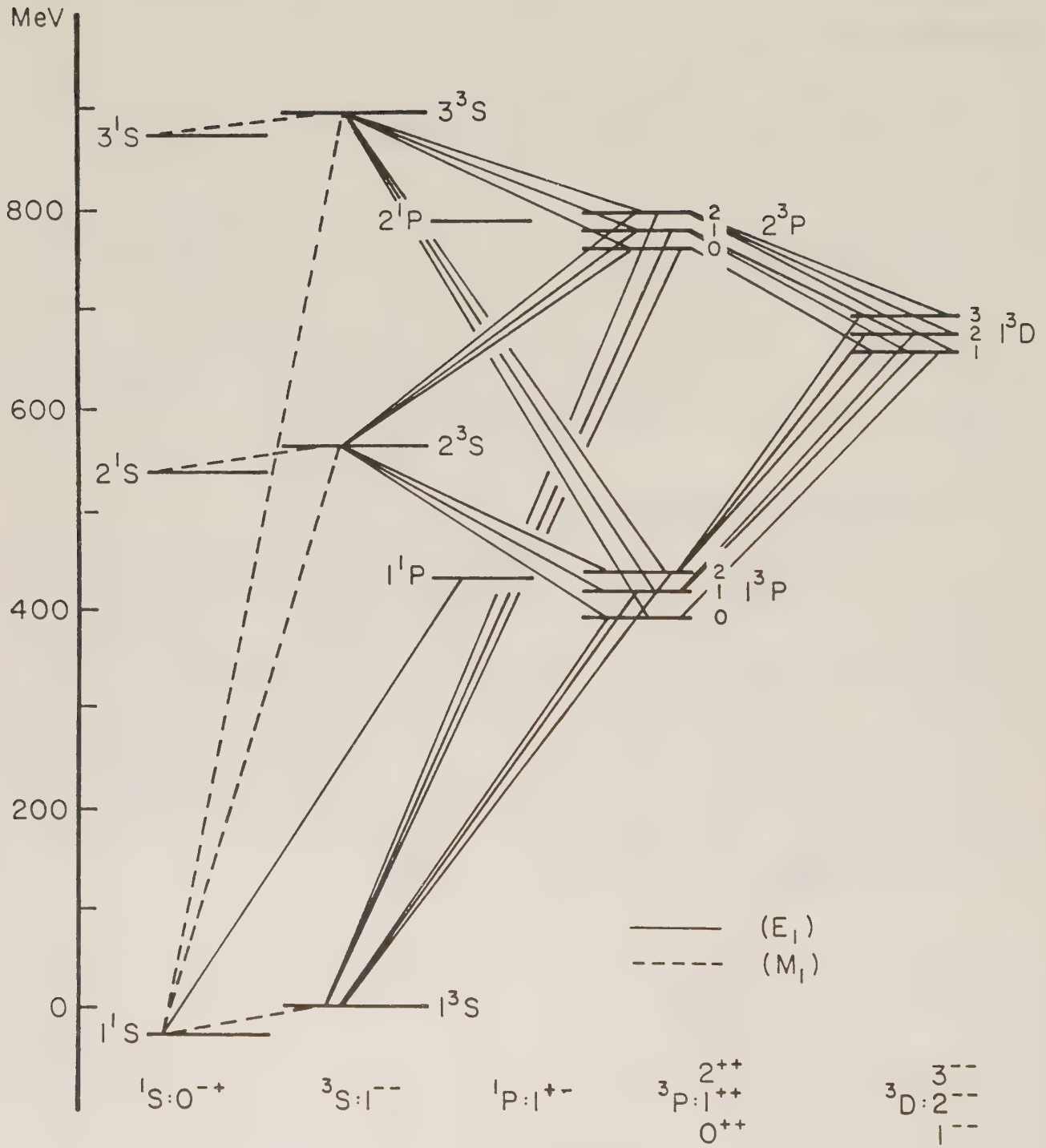


Fig. 2.8 Photon transitions in the bottomonium system.

k_γ the photon energy, J_f the total angular momentum of the final state, and $\langle f|r|i \rangle$ the matrix element of the coordinate between initial and final states⁺). Since photon energies and wave functions for $b\bar{b}$ states are calculable in potential models, these rates can be predicted. For example, the photon energies are expected to be around (110,130,150) MeV for the transition $T' \rightarrow \gamma 1^3P_J$ and (80,100,120) MeV for $T'' \rightarrow \gamma 2^3P_J$ (with $J=2,1,0$), thus estimating E1 transition rates at the order of a few keV. This leads to branching ratios in the 5-10% range for the individual transitions.

Magnetic dipole (M1) transitions in the $b\bar{b}$ system are suppressed. For a M1 transition it is required that $L_i=L_f$. In addition parities of the initial and final states are the same. Examples are the transitions between 3S_1 and 1S_0 states. The transition rate for the process $n^3S_1 \rightarrow \gamma n'^1S_0$ is given in a non-relativistic approximation by [KK 79]:

$$\Gamma(n^3S_1 \rightarrow \gamma n'^1S_0) = 4\alpha e_b^2 (k_\gamma^3/3m_b^2) |I|^2 \quad (2.37)$$

where I denotes the spatial overlap integral between triplet and singlet S-states. In this approximation $|I|^2=1$ if $n=n'$ as in the case of $T \rightarrow \gamma \eta_b$, and 0 if $n \neq n'$ as for hindered transitions like $T' \rightarrow \gamma \eta_b$. If $k_\gamma \approx 50$ MeV one expects a rate of $\Gamma(T \rightarrow \gamma \eta_b) \approx 5 \times 10^{-3}$ keV. However, relativistic corrections modify the rates in eq. (2.37), leading to small overlap integrals at the order of a few percent for $n \neq n'$ transitions. For $n=n'$ transitions $|I|^2$ still remains of the order one [ZB 83]. Since Γ_{M1} also contains the photon energy as k_γ^3 , one expects larger rates for the hindered transitions ($n'=n+1$). Using our previous examples we find that for photon energies of 600 MeV and 50 MeV, respectively, the rates are related by $\Gamma(T' \rightarrow \gamma \eta_b) \approx 50 \cdot \Gamma(T \rightarrow \gamma \eta_b)$.

From eq. (2.37) we can derive a scaling relation for M1 rates in the Ψ and T systems:

$$\Gamma(T \rightarrow \gamma_1 \eta_b) / \Gamma(\Psi \rightarrow \gamma_2 \eta_c) \approx (m_c^2/m_b^2) \cdot (e_b^2/e_c^2) \cdot (k_1^3/k_2^3) \quad (2.38)$$

In chapter V we summarize predictions for masses, 3P -state fine splittings, and transition rates of various models in the $b\bar{b}$ system in comparison with measurements.

⁺) In non-relativistic potential models the matrix elements $\langle f|r|i \rangle$ are the same for all three 3P_J states, while in models including relativistic corrections they differ by a few percent [MR 83].

III. DESCRIPTION OF THE EXPERIMENT

III.1 The Cornell Electron Storage Ring

The Cornell e^+e^- storage ring CESR started operation in late 1979 after a construction period of two years. Even before the discovery of the Υ states, the plan was to build a storage ring in the energy domain between 4 GeV and 8 GeV per beam with high luminosity ($10^{32} \text{ cm}^{-2}\text{s}^{-1}$ at 8 GeV) and small machine energy spread. Only the energy range between 4.6 GeV and 5.8 GeV has been explored up to now.

Fig. 3.1 shows a schematic layout of CESR. The storage ring with a mean radius of 122 m is installed in the tunnel of the 10 GeV synchrotron, which has a mean radius of 120 m. Two transfer lines in the east and west connect the storage ring with the synchrotron. CESR is operated in a single bunch mode and runs presently in the 3 cm optics (the vertical beta function at the interaction region). CESR has two interaction regions. In the south area the CLEO detector operates. It is a big universal magnetic detector with emphasis on momentum measurement for charged particles (superconducting solenoid plus drift chambers) and particle identification (dE/dx). In the north area the CUSB detector operates. It is a nonmagnetic calorimeter consisting mostly of NaI(Tl) crystals. While the main task of the CLEO detector is the reconstruction of charged particles, the CUSB detector is optimized for the analysis of photons and therefore well suited to search for the 3P states of the $b\bar{b}$ system.

The relevant machine parameters of CESR are summarized in table 3.1. For comparison the parameters for DORIS are also listed.

Since the machine resolution of CESR is much better than that of DORIS ($\sigma_E = 3.7 \text{ MeV}$ vs 10 MeV at $E = M_{\Upsilon} = 9.4 \text{ GeV}$), the ratio of resonance to continuum data is a factor ~ 2.4 higher at CESR. This leads to a factor 2.4 longer time for data taking at DORIS to gain the same 'on resonance' statistics.

For the higher lying Υ states the resolution scales as follows:

$$\sigma_E(\text{res}) = \sigma_E(\Upsilon) \cdot (M_{\text{res}}^2 / M_{\Upsilon}^2) \quad (3.1)$$

To keep the beam-gas background small it is important to have a stabilized vacuum of $\lesssim 10^{-9}$ at the interaction region. This is achieved by two vacuum pumps on both sides of the interaction region.

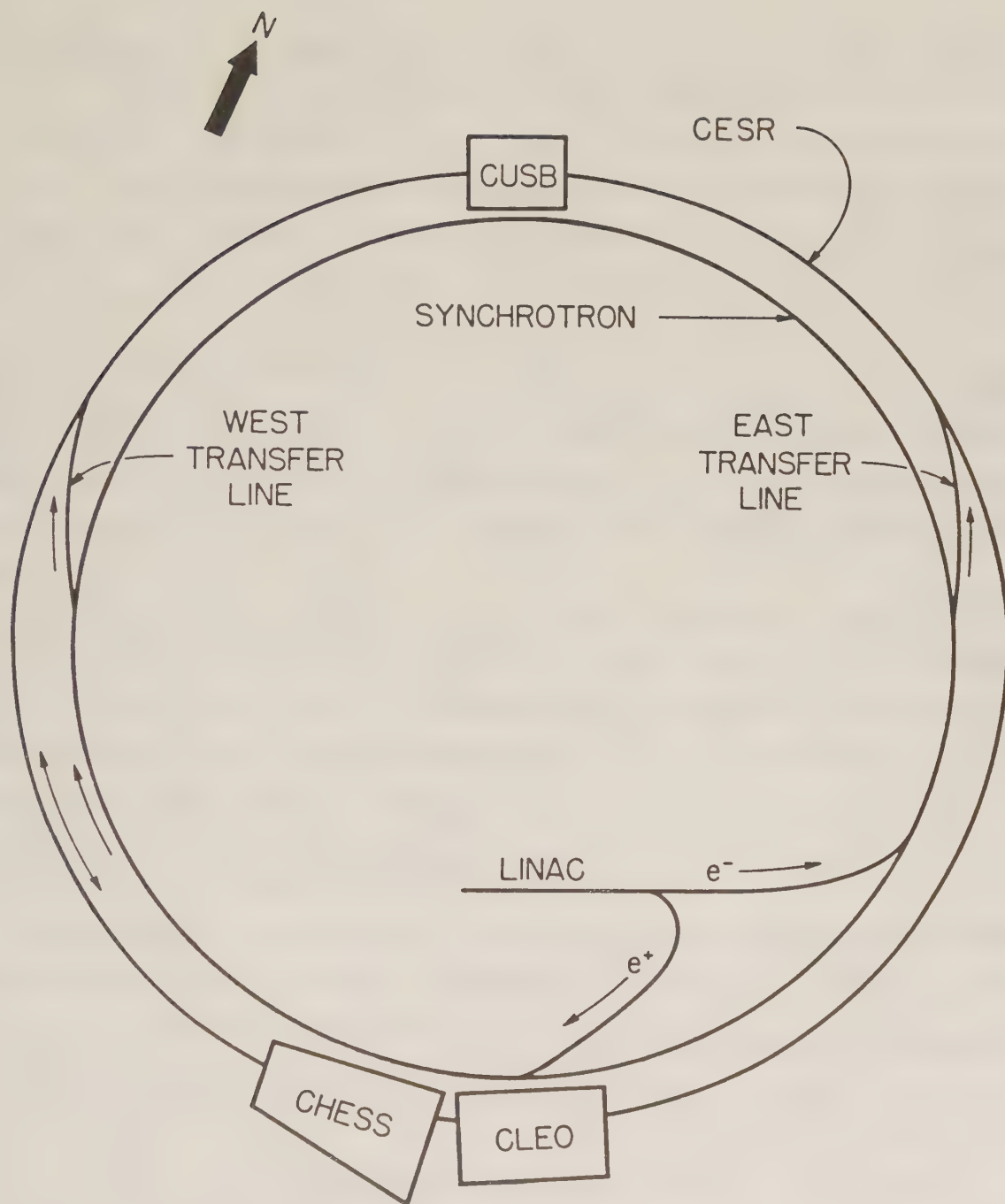


Fig. 3.1 Schematic layout of the Cornell Electron Storage Ring (CESR).

Table 3.1 Machine parameters of CESR in comparison to DORIS

Machine parameters	CESR	DORIS	Dimension
mean radius	122	50	[m]
circumference	768	300	[m]
number of bunches	1	1	-
beam crossing time	2.56	1	[μ s]
$E_{\max}$	2x8	2x5.6	[GeV]
bunch energy spread σ_E (at M_T)	3.7	10	[MeV]
bunch size $\sigma_x, \sigma_y, \sigma_z$	.5, .1, 20	--	[mm]
maximal beam currents	2x16	2x25	[mA]
best $\beta_v^{*a)}$	3	4	[cm]
$L_{\max}$ at T'	1.9×10^{31}	3×10^{31}	[$\text{cm}^{-2} \text{s}^{-1}$]
$L_{\max}$ at T''	1.6×10^{31}	--	[$\text{cm}^{-2} \text{s}^{-1}$]
$\langle \int L dt \rangle$ at T'	400 (600) ^{b)}	700	[$\text{nb}^{-1}/\text{day}$]
$\langle \int L dt \rangle$ at T''	400 (600) ^{b)}	--	[$\text{nb}^{-1}/\text{day}$]
$\langle \int L dt \rangle$ at T'''	600 (900) ^{b)}	--	[$\text{nb}^{-1}/\text{day}$]
beam life time τ_b	3	2	[hours]
filling time τ_f	45-60	<5	[min]
background at interaction point	<.1	~2	[R/day]

a) Vertical beta function at the interaction region.

b) The numbers in brackets refer to the maximum luminosity accumulated per day.

III.1.1 Injection and Filling Scheme

A novel scheme has been adopted for positron accumulation and filling since there is no intermediate accumulator and the primary positron intensity is very low. Positrons are produced conventionally: electrons are accelerated in the first half of a LINAC up to 175 MeV, hit a target of high density (e.g. tungsten), and create positrons by conversion of Bremsstrahlungsquanta. The positrons are collimated, focussed and injected into the synchrotron after a preacceleration to 200 MeV in the second half of the LINAC. The yield is only ~1%. To increase the intensity of positrons the continuous electron beam in the LINAC is modulated such that 60 evenly spaced bunches of positrons 42 ns apart are injected into the synchrotron. The 60 bunches are accelerated close to the final energy and are injected in a single turn into the storage ring. This process is repeated at 60 Hz several times, so that successive bunch trains from the synchrotron are laid on top of the 60 bunches circulating in the storage ring. To keep losses and the positron phase space relatively small, a maximum of 10^{-2} mA per bunch are accumulated. As the storage ring has a circumference of 61/60 of that of the synchrotron the 61st position remains empty.

At this point the bunches are transferred back into the synchrotron one at a time. After circulating them an appropriate number of times they are reinjected into the storage ring with an appropriate phase advance such that they all coalesce into a single bunch on the 61st position. Due to transfer losses only about half of the positrons are contained in the coalesced single bunch. The entire procedure is repeated several times until the desired positron current (~16 mA) is achieved.

Electrons are accelerated and stored conventionally in a single bunch. Electrostatic separator plates prevent interaction losses during filling. After fine tuning the beam energies the separator plates are turned off and the machine is ready for data taking⁺⁾ . The entire filling procedure takes about 45 min. The beams have typical lifetimes of ~3 hours. Fig. 3.2 shows for example the time dependence of the beam currents and luminosity for a typical day obtained at the T'.

The beam energy is measured by means of a NMR probe sampling the field of a typical dipole, including corrections which come from currents in all

⁺⁾ Further details are discussed in [CL 77].

other magnets. The energy scale is obtained by surveying the fields from all magnets and computing $\int B \cdot dl$.

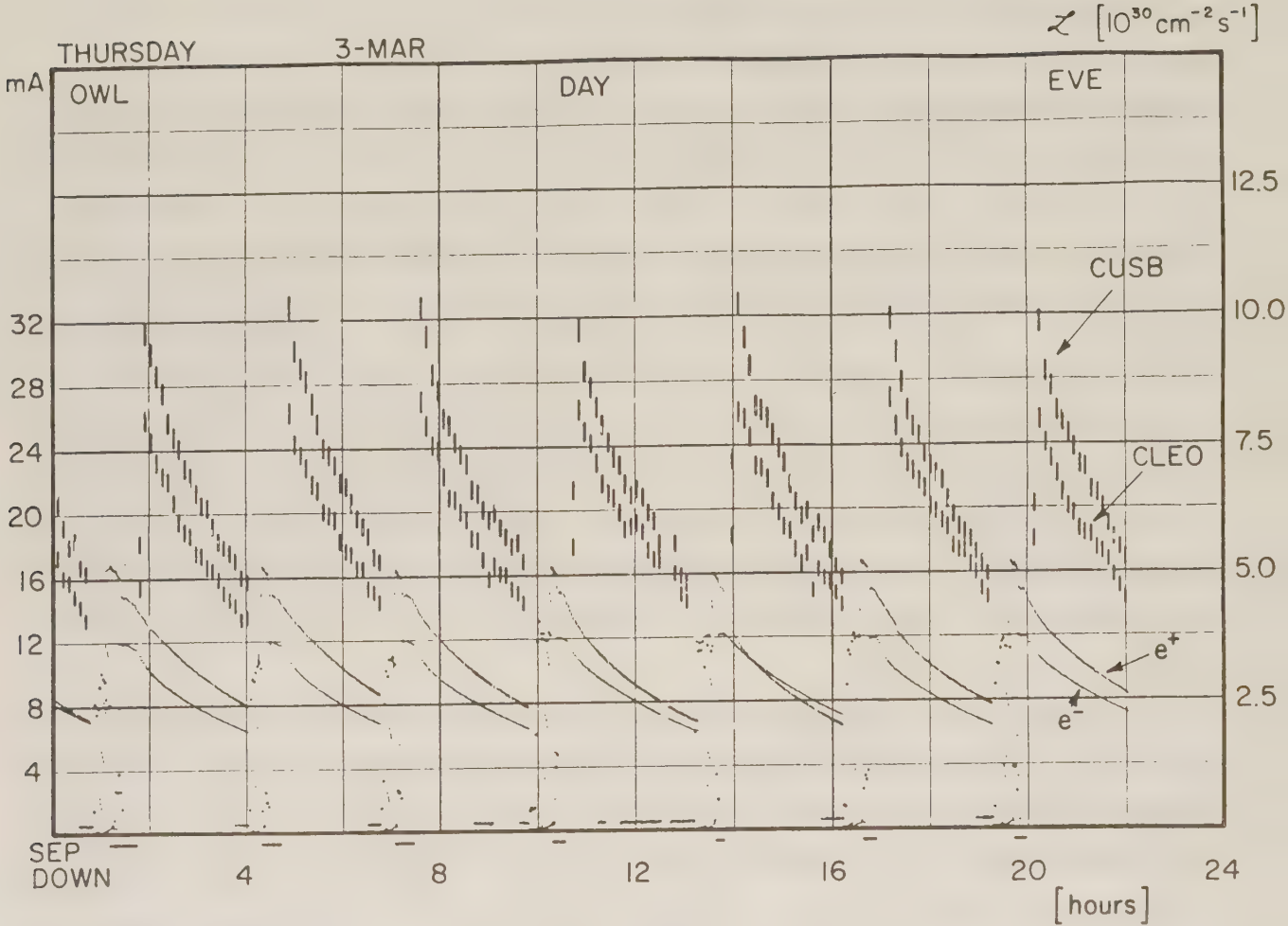


Fig. 3.2 Time dependence of beam currents and luminosity for a typical day at CESR running on the T' peak. The luminosity for CUSB is on the average 15% larger than for CLEO.

III.1.2 Luminosity

The total number N of reactions per unit time for a given process is proportional to the total cross section σ and the luminosity L :

$$N = L \cdot \sigma \quad (3.2)$$

L has the dimension $[\text{cm}^{-2} \text{ s}^{-1}]$ and is a quantity that depends entirely on

the properties of the beams. For a ring with colliding beams the luminosity is given by:

$$L = \frac{I_+ I_-}{4\pi\sigma_x\sigma_y \cdot e^2 \cdot n \cdot f} \quad (3.3)$$

I_+, I_- : stored positron, electron current

n : number of bunches

f : beam crossing frequency

e : electron charge

$4\pi\sigma_x\sigma_y$: beam cross section at interaction point (for head on collision⁺)

σ_x, σ_y : bunch spread in x and y direction assuming gaussian distributions

The luminosity shows a strong energy dependence. Fig. 3.3 displays the design luminosity versus beam energy for different e^+e^- machines. There are mainly two different effects limiting the luminosity in e^+e^- storage rings. For small energies $E < E_{\max}$, beam-beam interactions cause a limitation in luminosity⁺⁺). In this case L is proportional to E^4 and b_v^{*-2} (b_v^* : vertical beta function at the interaction region). At $E = E_{\max}$, the limiting factor comes from the available high frequency power $P_{\text{HF}} = U_0 I$ with $U_0 \sim E^4$. Thus L decreases like E^{-10} for energies $E > E_{\max}$ ⁺⁺⁺). At CESR the energy domain of the Υ states (9.4-10.5 GeV) lies below $E_{\max}$. From fig. 3.3 it is obvious that CESR is for the time being the place best suited for $b\bar{b}$

⁺) For a beam crossing under an angle 2δ the beam cross section changes to $4\pi\sigma_x(\sigma_y^2 + \sigma_1^2\delta^2)^{1/2}$, where σ_1 is the bunch length.

⁺⁺) Beam-beam interactions give a non-linear focussing which smears at the operating point in the betatron tune plane. The linear tune shift ΔQ is an approximate measure of this smearing. From practical experience with e^+e^- storage rings it is known that for $\Delta Q_{\max} \gtrsim .02-.04$ the beams blow up in cross section and become unstable. This limits the stored currents and in turn the luminosity. The currents in this case are given by (see e.g. [Wn 73]):

$$I \sim (\gamma/b_v^*) \cdot \pi\sigma_x\sigma_y \cdot e \cdot n \cdot f \cdot \Delta Q_{\max}$$

with $\gamma = E/m_e c^2$ and $\sigma_x\sigma_y \sim E^2$, giving $L \sim E^4$.

⁺⁺⁺) In this case the losses due to synchrotron radiation $\sim E^4$ cannot be compensated by the RF-power.

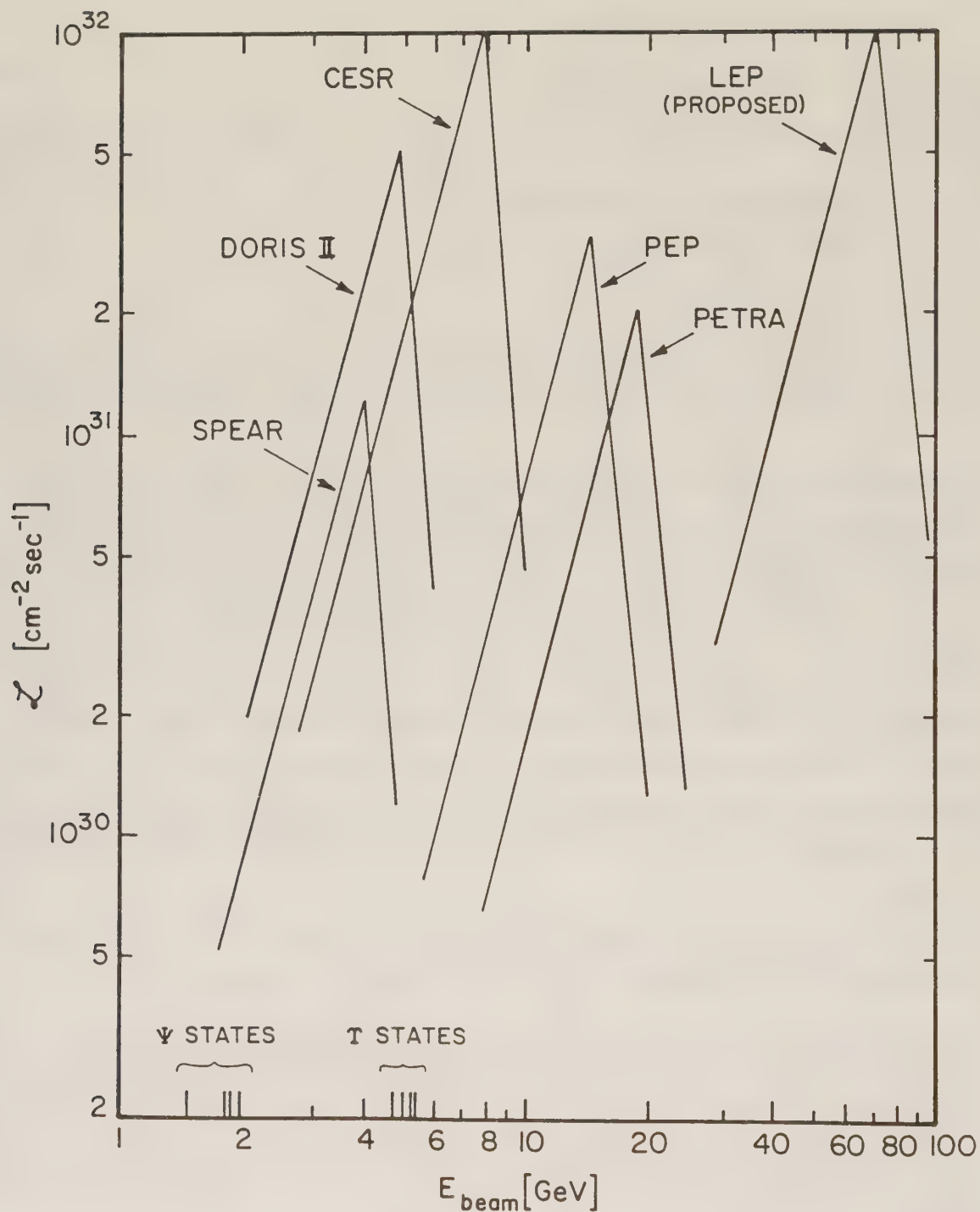


Fig. 3.3 Energy dependence of the luminosity for different e^+e^- storage rings.

studies. The design luminosity at the $\Upsilon(4S)$ is $4 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$. Until the Fall of 1981 only a peak luminosity of $3 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ at the $\Upsilon(4S)$ was obtained. After the installation of minibeta quadrupoles in the Fall of 1981 the peak luminosity was increased to $1.6 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ at the Υ'' giving an average integrated luminosity of 400 nb^{-1} per day (see table 3.1). Fig. 3.4 shows the development in integrated luminosity over the past two years.

For the future it is planned to increase the luminosity by another factor of ~ 10 (2000 nb^{-1} per day at the Υ) by using a new LINAC to reduce the filling time, installing microbeta quadrupoles and operating the machine in a multibunch mode.

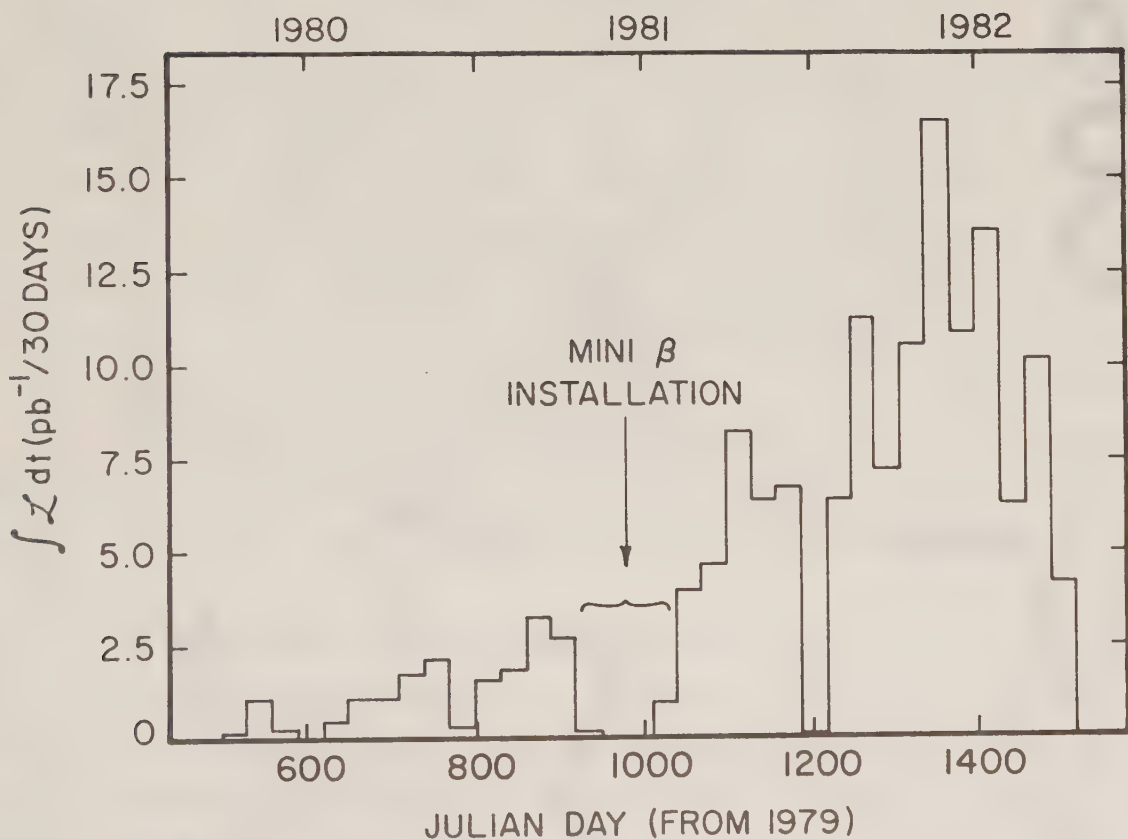


Fig. 3.4 Integrated luminosity per 30 days vs. time accumulated by CUSB since the beginning of 1980. The substantial increase starting in late 1981 is due to the installation of mini-beta quadrupoles.

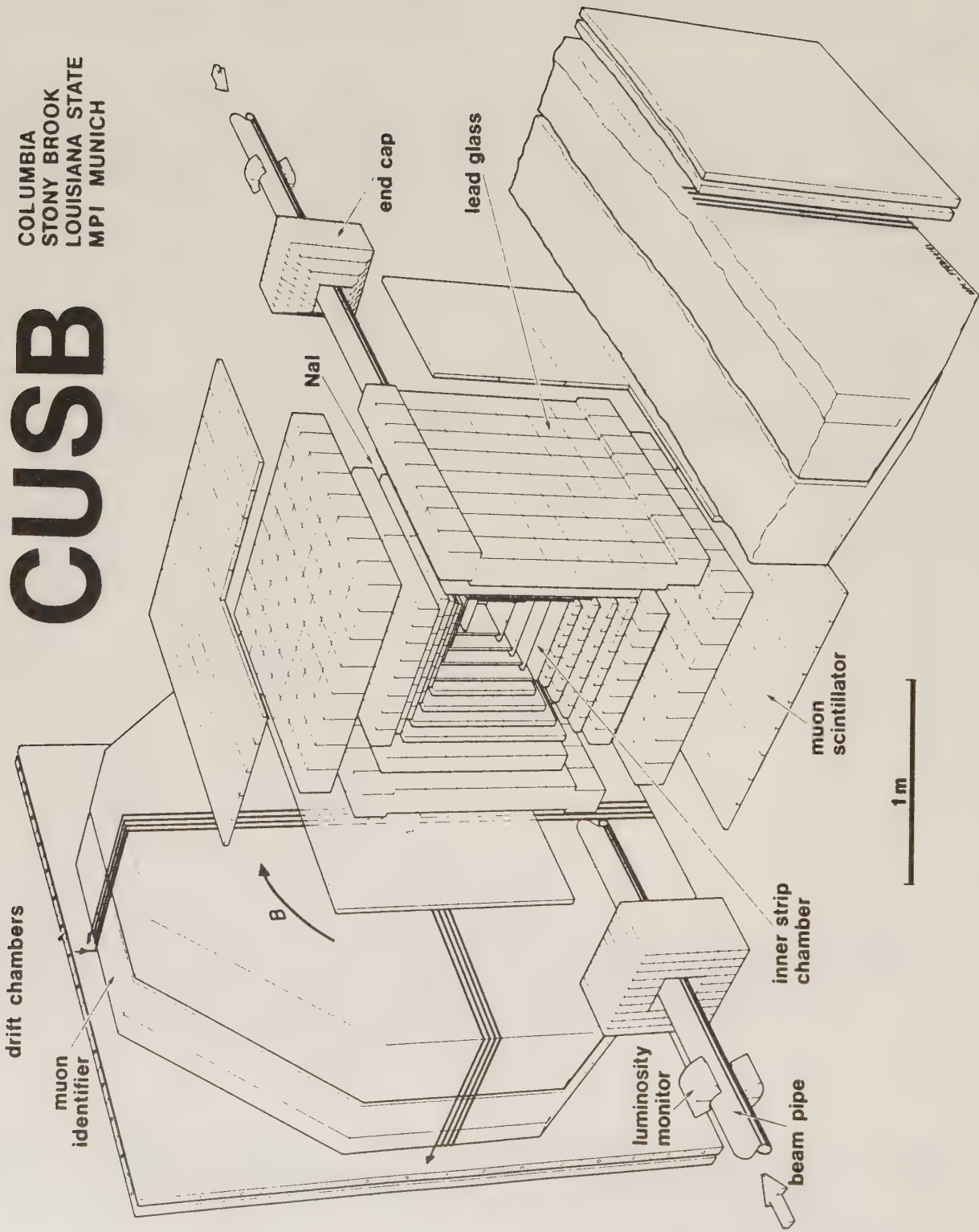


Fig. 3.5 Exploded view of the CUSB detector. For the graphical display the endcaps are pulled out.

III.2 The Detector

The CUSB detector is a nonmagnetic electromagnetic shower calorimeter with a square geometry covering approximately 85% of the entire solid angle. Fig. 3.5 shows an exploded view of the detector. The main parts are:

- i) an aluminum beam pipe 2.3 mm thick and 15.3 cm in diameter.
- ii) the inner strip chamber (ISC) detector made of proportional chambers to discriminate charged from neutral particles.
- iii) the central detector (CD) consisting of an array of 332 NaI(Tl) crystals and 256 blocks of lead glass for measuring the energy of electromagnetic showers to better than 6%. The NaI crystals are stacked in 5 layers with proportional strip chambers between them to determine the shower position. The lead glass is arranged in four 8x8 matrices surrounding the NaI.
- iv) two endcaps (EC), each consisting of 84 NaI(Tl) crystals, which increases the solid angle up to 85% of 4π sr (in fig. 3.5 pulled apart).
- v) a set of scintillation counters surrounding the CD on 4 sides, used to trigger on back-to-back muons.
- vi) two muon filters on the south and north side consisting of a stack of iron and drift chambers. The coverage is 25% of the total solid angle.
- vii) the luminosity monitors, a set of lead-scintillator sandwich shower counters which sit next to the mini beta quadrupoles and are used to measure the luminosity using small angle Bhabha scatters.

The whole detector is enclosed in an environmental hut to protect the NaI. The air is dehumidified and the temperature is regulated to $\pm 1^\circ$ C in order to minimize the temperature drift of the NaI (.4% per $^\circ$ C).

III.2.1 The Inner Strip Chamber Detector

The ISC detector replaced the original inner drift chambers (see [Ms 83]) in order to install endcaps that increased the coverage in solid angle for calorimetry from 60% to 85% of 4π sr. Special care has been taken in the construction to minimize both the material seen by traversing particles and the dead space at the corners.

The inner strip chamber (ISC) detector is needed for two reasons:

- i) to determine the trajectories of charged particles
- ii) to provide a track veto for neutral particles in the central detector (e/ γ separation).

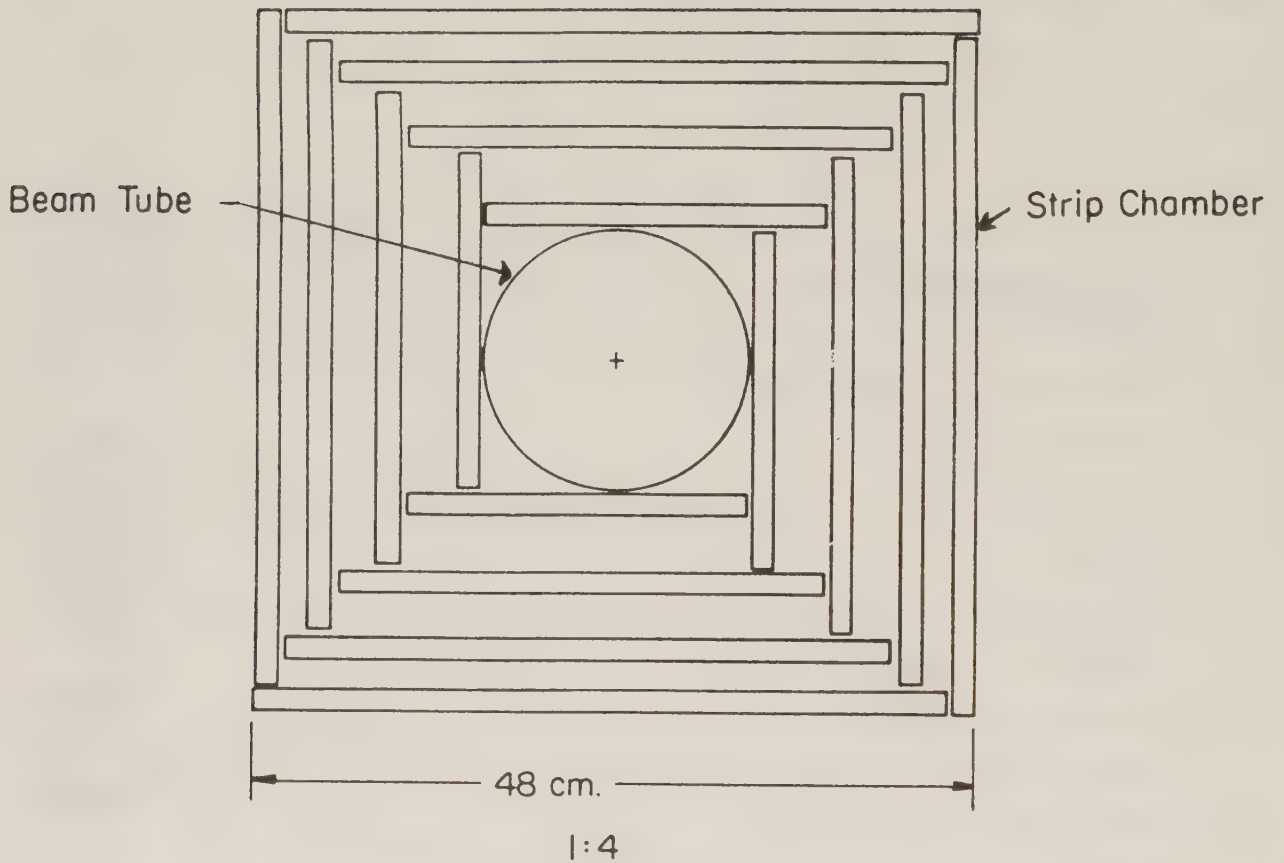


Fig. 3.6a Transverse view of the inner strip chamber detector.

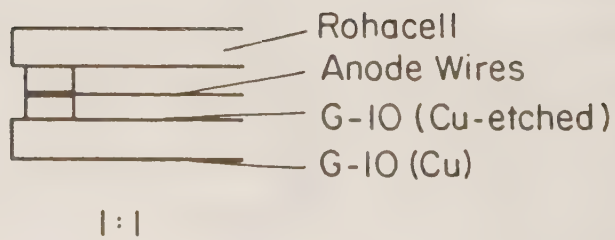


Fig. 3.6b Construction details of a strip chamber.

III.2.1.1 Technical Description

The arrangement of the ISC detector in the view transverse to the beam is shown in fig. 3.6a (for the parallel view see fig. 3.14b). The ISC detector consists of four identical quadrants of proportional chambers surrounding the beam pipe. Each quadrant has four chambers, varying in size from $23 \times 21 \text{ cm}^2$ to $46 \times 44 \text{ cm}^2$, with analog readout of the cathode planes. The distance to the interaction point ranges from 100 mm to 215 mm. The chambers are arranged such as to overlap at the edges, thus covering the azimuthal angle ϕ without gaps. The coverage for the polar angle θ ranges from 50° to 130° allowing a perfect match to the profile of the endcap crystals (see fig. 3.14b). The total solid angle covered by the ISC detector is 62% of $4\pi \text{ sr}$. The relevant parameters for the ISC detector are listed in table 3.2.

Fig. 3.6b displays the typical cross section of a strip chamber. Each strip chamber is made of two rectangular 5 mm thick sheets of Rohacell 51 (of 50 mg/ccm density) sandwiched between $100\mu\text{m}$ thick foils of G-10, the outer sides of these foils being clad with $17 \mu\text{m}$ copper. One of the copper clad foils is etched such that parallel cathode strips of 9mm width spaced by 1mm are obtained. In each chamber there are two such planes with cathode strips, where one plane has strips parallel and the other strips orthogonal to the beam direction, defining the transverse view and side view, respectively. This arrangement therefore allows the measurement of a space point in each strip chamber.

Both sandwiches are held together by thin frames also made of Rohacell which define a 7 mm gap between them. The plane of anode wires is located in the center of this gap. The wires, made of $20 \mu\text{m}$ gold plated tungsten, are fixed to these frames at a pitch of 3mm. The wires run parallel to the beam axis. The values chosen for strip and gap widths are optimized to obtain a good spatial resolution with a relatively small amount of channels to be read out.

The assembly and precise positioning of the four chambers in a quadrant is achieved by small Rohacell spacers. The total amount of material corresponds to 3.2% of a radiation length (rl) per quadrant for normal incidence. The final positions have been measured with 1 mm precision. Further fine adjustments were done with cosmic ray muons and Bhabha scattering events.

Table 3.2 Physical parameters of the inner strip chambers (ISC's)

1. Geometry:

chamber	sensitive area [cm ²]	distance to beam [cm]
1	22.5x21	9.5
2	32.5x30	14.9
3	40.0x37	19.4
4	45.5x44	22.8

2. Material in the ISC:

material	thickness [mm]	radiation length [%]
Cu	4x.017	.47
G-10	4x.1	.20
Rohacell	2x5	.12
Argon-Ethane	1x7	.003
W	1x.02	.003
Epoxy	4x.05	.04

This gives a total of ~0.8% of a r.l. per strip chamber at normal incidence.

3. General Properties:

parameter	numerical value
coverage ϕ :	2π without gaps
θ :	$47^\circ - 132^\circ$
$\Delta\Omega/4\pi$:	62%
readout:	cathode readout in 2 planes
cathode stripwidth:	9 mm + 1 mm gap
gap width:	7 mm
anode wires:	gold plated tungsten, $\phi=20\mu$
anode wire spacing:	3 mm
operating HV:	2 - 2.4 kV
gas mixture:	50% Ar and 50% ethane
gas gain:	$\sim 10^4$
ADC channels:	1092
efficiency:	99.3% per chamber
position resolution σ_z (res):	0.8 mm along the sense wire
σ_t (res):	1.2 mm perpendicular to sense wire
pulse height matching x,y:	$\sim 10\%$ (rms)
peak of dE/dx distribution:	600(425) ADC counts for Bhabhas(muons)
FWHM of dE/dx distribution:	560(380) ADC counts for Bhabhas (muons)
track matching:	>95% for 2 tracks/quadrant
track matching:	>89% for 3 tracks/quadrant

III.2.1.2 Chamber Operation

The chambers are operated with a gas mixture of 50% argon and 50% ethane. High voltage of 2.0-2.4 kV is coupled via 1 M Ω resistors to the anode wires as shown in fig. 3.7a. The typical chamber gain is $1-2 \times 10^4$. During filling of the storage ring the high voltage is automatically lowered by 800 V to avoid damage from high particle fluxes. During operation the currents per chamber are typically 1 μ A.

III.2.1.3 Electronic Readout

Fig. 3.7a also shows the readout schematics. To achieve the necessary compact assembly of the strip chambers and endcaps the 1092 cathode strips of all 16 chambers are connected by very thin (0.8 mm diam.) 50 Ω coaxial cables of 2 m length to current amplifiers, located in the experimental hut. The amplifiers (see circuit diagram in fig. 3.7b) are operated at a low voltage of +5.0/-5.0 V and have a feedback resistor of 10 k Ω . They are followed by cable drivers. The total gain is ~ 300 .

The amplified signals are fed via 30 m, 100 Ω twisted pair cables into gated charge-sensitive analog-to-digital converters (ADC's). The ADC's, located in the electronics hut, are 12 bit high-gain units with differential input. The ADC gate is opened during each beam crossing for 200 ns. If no trigger signal is generated within 600 ns the ADC's are reset by a fast clear signal. In the case of a trigger the digitized pulses are transmitted through the so-called data transport system to a PDP 11 computer, which writes the pulse heights of all 1092 ADC's on magnetic tape if the trigger passes a software filter (see section III.3.1). The pedestal distribution for 200ns integration time typically peaks at ADC channel number 250 with a standard deviation $\sigma=5$ counts.

The ISC electronic system has three free parameters, the feedback resistors, the ISC high voltage and the amplifier low voltage which changes slightly the gain of the cable drivers. The values given above were optimized:

- i) to obtain a high gas amplification
- ii) to get a good signal-to-noise ratio
- iii) to locate the peak of minimum ionizing tracks at ADC channel ~ 400 after pedestal subtraction, a value which is well above pedestal but small enough to be sensitive over a large range to Landau fluctuations for electrons, converted photons, and highly ionizing slow particles.

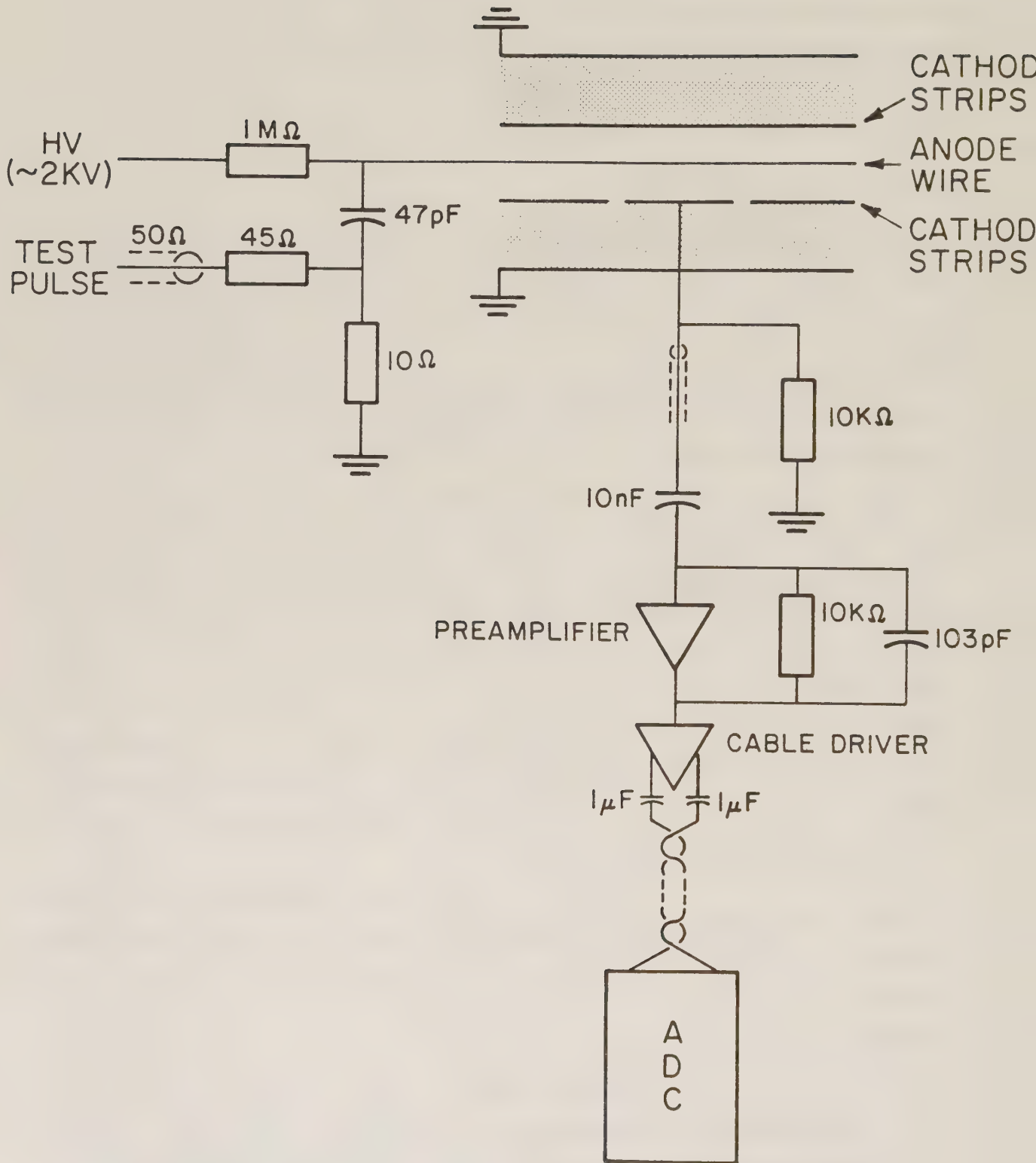


Fig. 3.7a Schematics of the signal readout and the couplings to the high voltage and test pulser for the inner strip chambers.

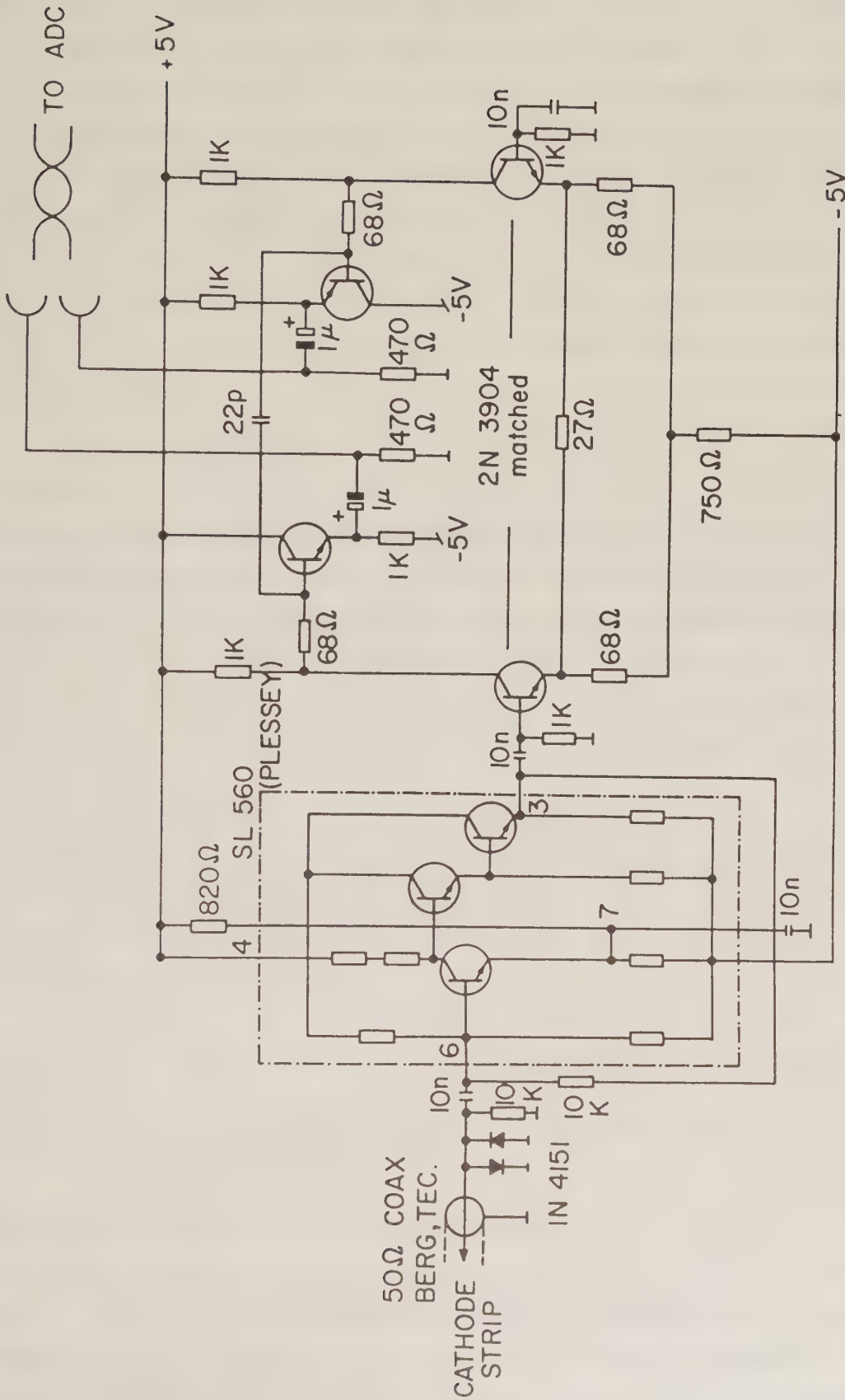


Fig. 3.7b Circuit diagram of the preamplifier and cable driver for output signals of the inner strip chambers.

In order to test and calibrate each channel in the readout system (cathode strip, amplifier, and ADC) each chamber can be pulsed with a test pulser, which is coupled to the anode wires (as shown in fig. 3.7a).

III.2.1.4 Chamber Monitoring

In order to locate dead or noisy channels the 16 chambers are constantly monitored both online and offline. For every run all observed hits (i.e. any pulse on a cathode strip above 60 ADC counts after pedestal subtraction) are histogrammed online, summing over all cathode strips in each view of each individual chamber. Optionally also individual events can be displayed online on a TV monitor. Offline, about once a month, ~5000 Bhabha scatters are analyzed in order to check for each chamber the distributions for hits recorded on individual cathode strips, pulse heights, pulse height matchings of the side and transverse view, and residuals of the fitted-minus-observed cluster position. In addition efficiencies for space tracks and the position of the interaction vertex are determined. The results of this analysis are used in turn to cross-check the calibration constants. The calibration constants have been adjusted such that for each chamber the pulse heights per cathode strip were nearly equal. To update the constants, the 16 chambers are pulsed with the test pulser, which produces the same pulse shape as the induced signal on a cathode strip.

In the two years of operation the ISC's proved to be very reliable. The average signal decreased by ~15%, which was compensated by raising the ISC high voltage by ~15 V. Under noisy beam conditions, two of the innermost chambers drew current of ~10 μ A. To avoid damage to these chambers, the high voltage was lowered until the current dropped below 5 μ A.

III.2.1.5 Offline Pulse Height Analysis

To perform track reconstruction in the ISC's one first has to search for all ISC clusters. As a first step, the pedestal subtracted pulses from each chamber in each view are sorted according to their pulse height. Any pulse above a threshold, set at ADC channel number 60, is used as a seed to form a cluster, which is defined as a pattern of n adjacent strips with pulse heights above threshold. We can restrict n to ≤ 3 since for our geometry a traversing charged particle (δ -rays excluded) will in general induce signals on not more than 3 cathode strips. Thus starting with the

highest seed we include both neighbors if their pulse heights are above threshold and if they have not been already associated with a different cluster. However, to reduce the error in position measurement for clusters, consisting of only one strip or two strips with nearly equal pulse heights, we in addition include the neighbors below threshold if the pulse heights (after pedestal subtraction) are positive. This results in a distribution of 2% one strip, 88% two strip and 10% three strip clusters, as obtained from the analysis of tracks from Bhabha scatters. Patterns with 4 or more adjacent strips sometimes occur (<1%) due to δ -rays, ADC pickups, or splashes from beam-gas or beam wall interactions. Such patterns are grouped in clusters in the same way as discussed above.

For each cluster with the total pulse height P we calculate the center-of-gravity (cog):

$$\bar{x} = \sum_i (P_i x_i) / \sum_i P_i \quad (3.4)$$

Here x_i and P_i are the coordinate (strip center) and pulse height of the i -th strip where i runs over all (n) included strips. However, as shown in reference [En 81], the cog only gives an approximate position. To improve the resolution in position measurement we correct the cog $\bar{x}$ by a function $\Delta x(\bar{x}, n)$, which is the difference of the theoretically expected cluster position for the observed distribution of pulse heights and the corresponding position determined by the cog method. The expected cluster position is calculated from the electrostatic model of charge distributions as given in [En 81] using the geometric configuration of the ISC's. $\Delta x(\bar{x}, n)$ depends both on the position $\bar{x}$ and the number of strips per cluster, typically varying between 0 and 0.6 mm, where the average correction amounts to ~ 0.3 mm.

Fig. 3.8 shows the pulse height distribution P_c for muons and Bhabhas corrected for angular effects according to:

$$P_c = P / \sqrt[2]{(1 + \text{tg}^2 \phi_L + \text{tg}^2 \delta)} \quad (3.5)$$

where ϕ_L is the local azimuth angle defined by:

$$\text{tg} \phi_L := \min(|\cos \phi_L|, |\sin \phi_L|) / \max(|\cos \phi_L|, |\sin \phi_L|) \quad (3.6)$$

and δ is the projected dip angle:

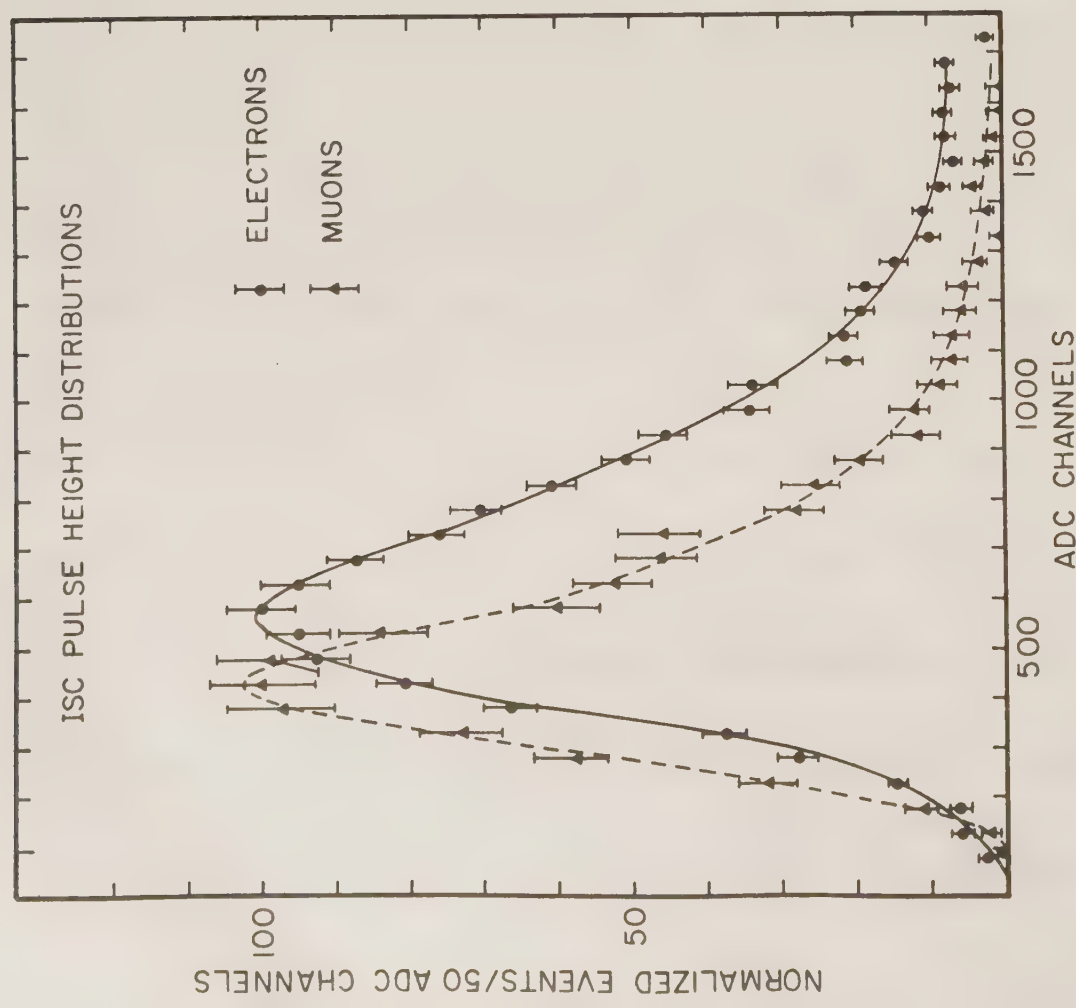


Fig. 3.8 Typical pulse height distributions for muons and Bhabha scatters in the inner strip chambers shown for a chamber in the side view. The pulse heights

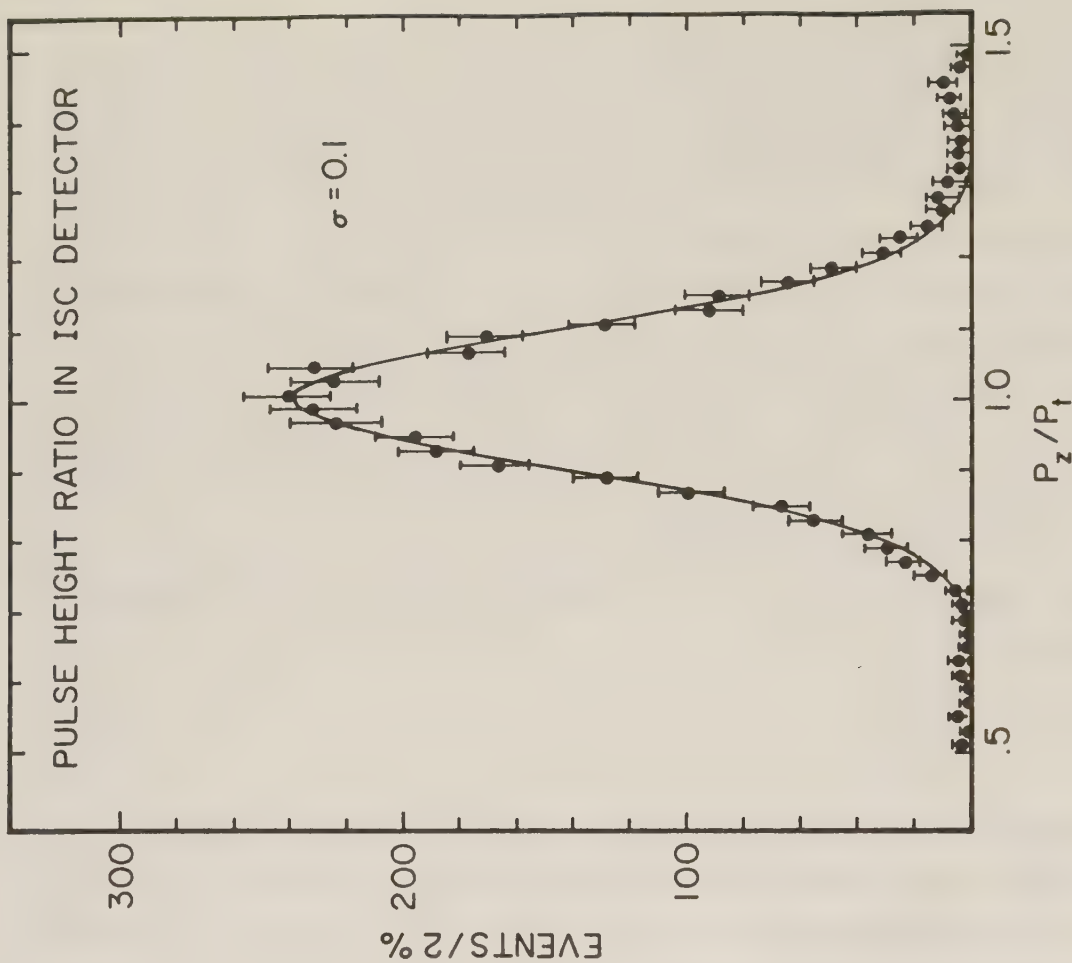


Fig. 3.9 Typical ratio for pulse heights of the side and transverse view of an inner strip chamber.

$$\operatorname{tg} \delta := \operatorname{ctg} \theta / \cos \phi_L \quad (3.7)$$

Note that the Bhabha peak is about a factor 1.4 higher than the minimum ionizing peak, as expected from the relativistic rise for 5 GeV electrons. The pulse height distribution for converted photons is expected to peak a factor 2 above the Bhabha peak, therefore allowing one to separate converted photons from Bhabhas or minimum ionizing particles. This fact is used in the selection criteria for $e e \gamma \gamma$ and $\mu \mu \gamma \gamma$ events (see chapter IV).

Figure 3.9 shows the ratio of pulse heights of the transverse and side view for back-to-back Bhabha scattering events. The pulse height matching has a typical spread of $\sigma \sim 10\%$.

III.2.1.6 Track Reconstruction

Track reconstruction is carried out first separately in each view. Starting with the first cluster in the outermost plane of a quadrant, we define a road pointing to the interaction vertex. For the transverse view the road widths are set to $\pm 8^\circ$ since the interaction vertex distributions in x and y are very narrow (see table 3.2). For the side view we use a road of $\pm 20^\circ$ due to the rather wide vertex distribution in z ($\sigma_z = 20\text{mm}$).

For all combinations of clusters within the road a line fit is carried out requiring 3 or 4 clusters per track. Lines with the best χ^2 are kept as tracks. The cut off is set at $\chi^2 = 5$ for 2 dof. If more than 1 track is found within a road but the tracks differ only in one or two clusters the one with the better χ^2 is selected. Tracks fitting four clusters are favored over tracks with only three clusters. The procedure is repeated for the remaining clusters in all planes and quadrants. Space tracks are found by comparing pulse height of tracks in both views. Those which have the best pulse height match in each chamber are combined to form a space track. The maximal allowed deviation in the pulse height matching is 30%. Tracks that do not match in space are kept separate. A problem for example occurs if two tracks overlap in one view. Then usually only one space track is found. On the other hand tracks penetrating at quadrant boundaries usually do not create a problem, since due to the geometry of the ISC one quadrant will always have clusters in at least 3 planes. However, the track finding is not optimized to cover secondary interactions like K^0 decays, because usually these tracks do not point to the interaction vertex and are therefore ignored.

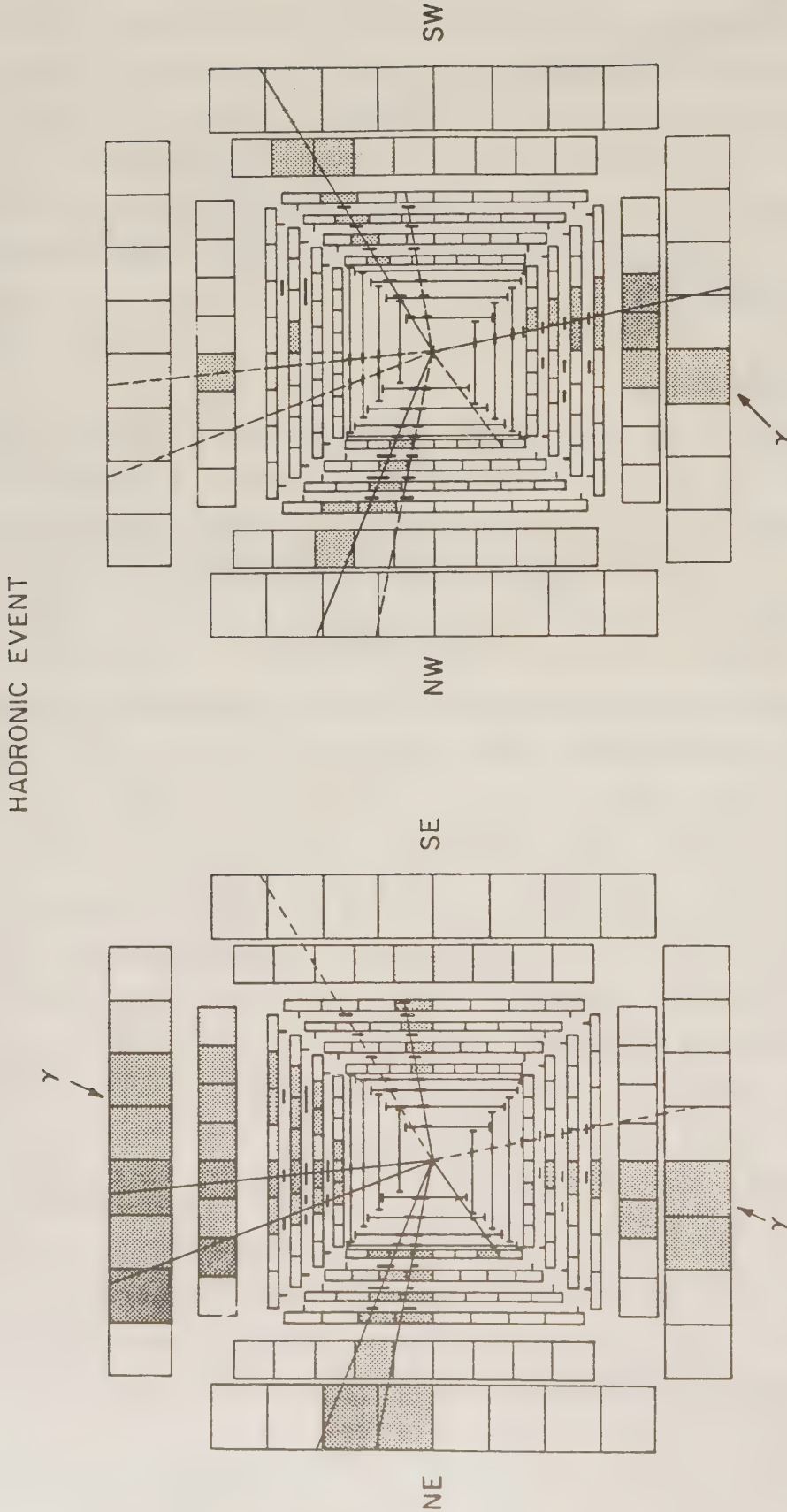


Fig. 3.10 A typical hadronic event from an π^0 decay in the central detector shown in the transverse view for the east and west polar half. Moving radially outward from the interaction region the plot shows 4 layers of inner strip chambers, 4 layers of thin NaI crystals, 1 layer of thick NaI crystals and one layer of lead glass blocks. The bars shown between the layers of thin NaI crystals indicate hits in the outer strip chambers. Solid lines represent tracks for charged particles in the polar half displayed while dashed lines correspond to tracks in the opposite half. Crystals with energy deposition (> 1 MeV) are shaded.

The single track finding efficiency is $>99\%$. The two and three track finding efficiencies for tracks separated by $\geq 2\text{cm}$ are still $>95\%$ and $>89\%$, respectively. Therefore Bhabha-like and muon-like events (e.g. $e\bar{e}\gamma\gamma$ or $\mu\bar{\mu}\gamma\gamma$) are fully reconstructed. Hadronic events are still up to $\sim 90\%$ fully reconstructable, since the mean multiplicity of 8 charged particles per event usually gives 1-3 tracks in a quadrant. As an example a typical hadronic event is displayed in fig. 3.10.

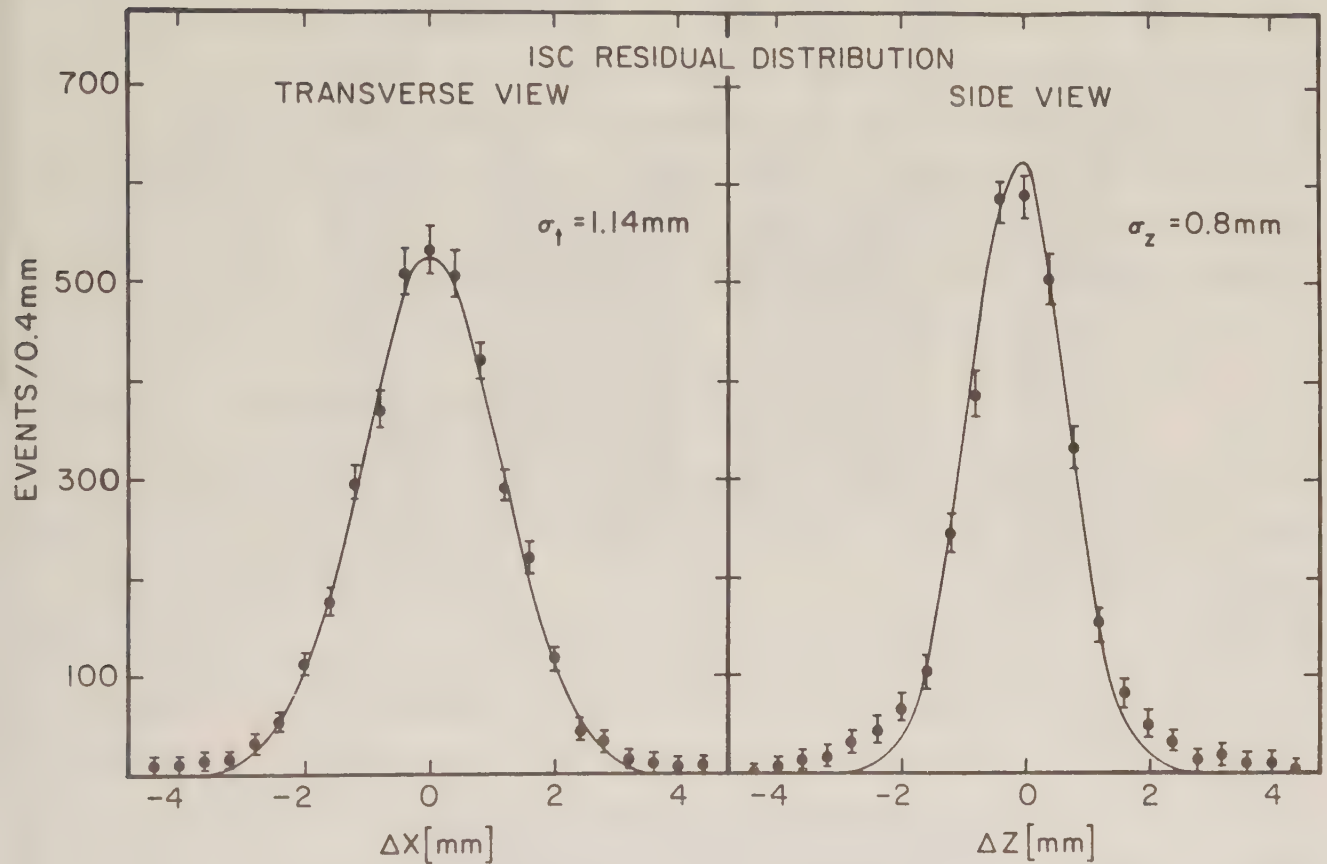


Fig. 3.11 Typical residual distribution of the fitted-minus-observed cluster position in the transverse and side view of an inner strip chamber.

Fig. 3.11 shows the distribution of the fitted-minus-observed cluster position (residuals) obtained by fitting two back-to-back Bhabha scatters through 8 chambers. We find a position resolution of $\sigma_t(\text{res})=1.2\text{ mm}$ in the transverse view and $\sigma_z(\text{res})=.8\text{ mm}$ in the side view. The worse resolution in the transverse view is caused by the 3 mm wire separation. The correction of cog for each cluster, discussed in the previous section, resulted in a gain in resolution of $\sim 50\%$. Further improvements (of another $\sim 30\%$) can be

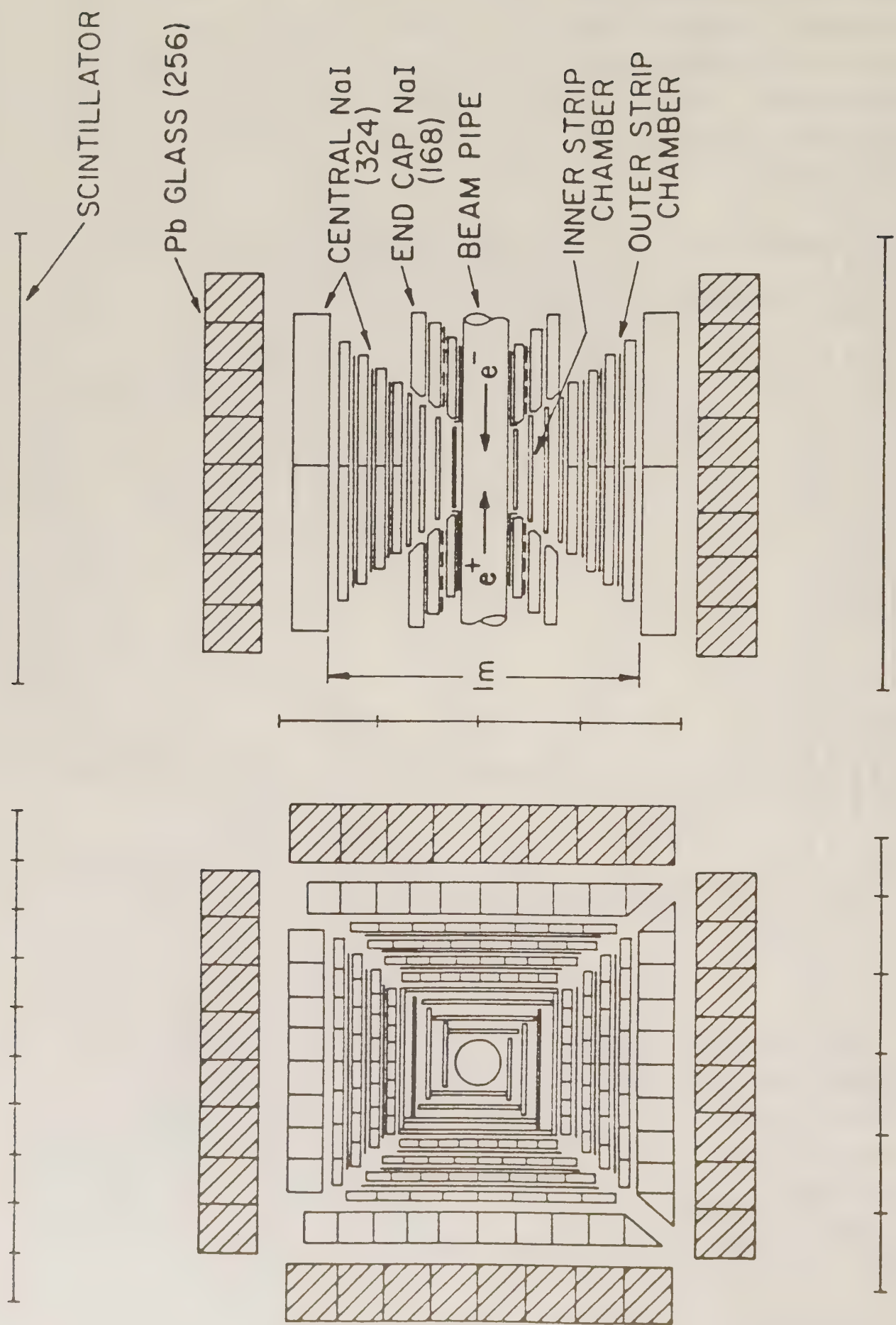


Fig. 3.12 Transverse and side view of the central detector.

achieved by plotting the residuals versus the observed cluster position and correcting the observed position for deviations from the expected line in the correlation plot [Aw 82]. However, for the present analysis a resolution of ~ 1 mm is sufficient. From the above position resolution we obtain an angular resolution of 1° in the azimuthal and 0.8° in the polar direction. For the vertex reconstruction a resolution of $\sigma_t(\text{vertex})=0.8$ mm in the transverse and $\sigma_z(\text{vertex})=15$ mm in the side view is obtained.

III.2.2 The Central Detector

Fig. 3.12 shows the central detector (CD) in the views both transverse and along the beam. The primary purpose of the CD is the measurement of electromagnetic showers in the energy range of 20-5000 MeV with very good resolution. The CD consists of five layers of NaI interspaced by strip chambers (OSC) and surrounded by arrays of lead glass Cerenkov counters (Pbc).

IV.2.2.1 The NaI-Calorimeter

The NaI (Tl) crystals are arranged in a square configuration of four quadrants. Each quadrant is divided into two identical polar halves at the median plane. Each half is segmented into 8 azimuthal sectors. Additionally, each sector is segmented into 5 radial layers, separated by 2.7cm. The first four layers are each 2.86cm thick while the fifth is 10.41cm thick, corresponding to 1.1 and 4.0 radiation lengths at normal incidence, respectively. This leads to a total of 8.4 r.l. for the NaI, which corresponds to 0.84 nuclear absorption lengths. The radial segmentation provides a very good means of separating hadrons from electromagnetic showers to better than 1:100.

To reduce the gaps at quadrant boundaries, 6 extra large crystals are positioned at the corners of each octant, where 2 of them have rectangular and 4 triangular cross sections (see fig. 3.12). Thus the coverage in solid angle is 60% of 4π , covering almost the full azimuthal region ϕ and polar angles θ between 46° and 134° . Losses at quadrant boundaries are typically at the order of 6% for Bhabha scatters and $\sim 10\%$ for low energy photons.

The crystals are right angular parallelepipeds with dimensions summarized in table 3.3. The radial planes increase in size going outward, so that each sector of the innermost plane subtends the same solid angle as the corresponding sector of the outer planes.

Table 3.3 NaI-crystal dimensions

Layer	Radial [cm]	Azimuthal [cm]	Polar [cm]
1	2.86	5.78	27.0
2	2.86	7.17	32.0
3	2.86	8.56	37.0
4	2.86	9.95	42.0
5	10.41	10.41	50.62

Table 3.4 Inactive material in the CD

Inactive Material in NaI Calorimeter	Thin Crystals (r.l.)	Thick Crystals (r.l.)
Reflective Paint	.2 mm (.1%)	.3 mm (.15%)
Plastic (on top and between crystals) (on bottom)	.1 mm (.02%) .2 mm (.04%)	.1 mm (.02%) .2 mm (.04%)
G-10 (on top and between crystals) (on bottom)	.4 mm (.2 %) .8 mm (.4 %)	.6 mm (.3%) .6 mm (.3%)
Al (on top and between crystals) (on bottom)	.1 mm (.11%) .2 mm (.22%)	.4 mm (.44%) .4 mm (.44%)+)
Epoxy (bottom only)	.1 mm (.02%)	.2 mm (.04%)

This gives a total of 6.2% of a r.l. for the inactive material in the entire NaI calorimeter at normal incidence.

+) Additional 3.2 mm aluminum plus 51 mm styrofoam in the top quadrant.

Inactive material in Pbc counters	between Pb blocks	between Pb and NaI
Mu metal	.4 mm (2.3%)	---
Al	.1 mm (.11%)	.1 mm (.11%)
Mylar	.03 mm (.01%)	.03 mm (.01%)
Plastic	.2 mm (.04%)	.2 mm (.04%)
Additional Al (only top quadrant)	---	3.2 mm (3.52%)
Styrofoam (only top quadrant)	---	102 mm (1.3%)

This gives ~0.2% of a r.l. for the inactive material in the Pbc counters. The entire inactive material is ~22% of a r.l. at normal incidence.

Since NaI is hygroscopic it has to be hermetically sealed. In this detector each crystal is covered with .1 mm reflective paint, then wrapped in a shock absorbing foil and finally hermetically sealed with an .1 mm thick aluminum foil. A group of 8 adjacent crystals is made light tight with .1 mm black polyurethane. For the optical readout a quartz window is glued to one of the end faces.

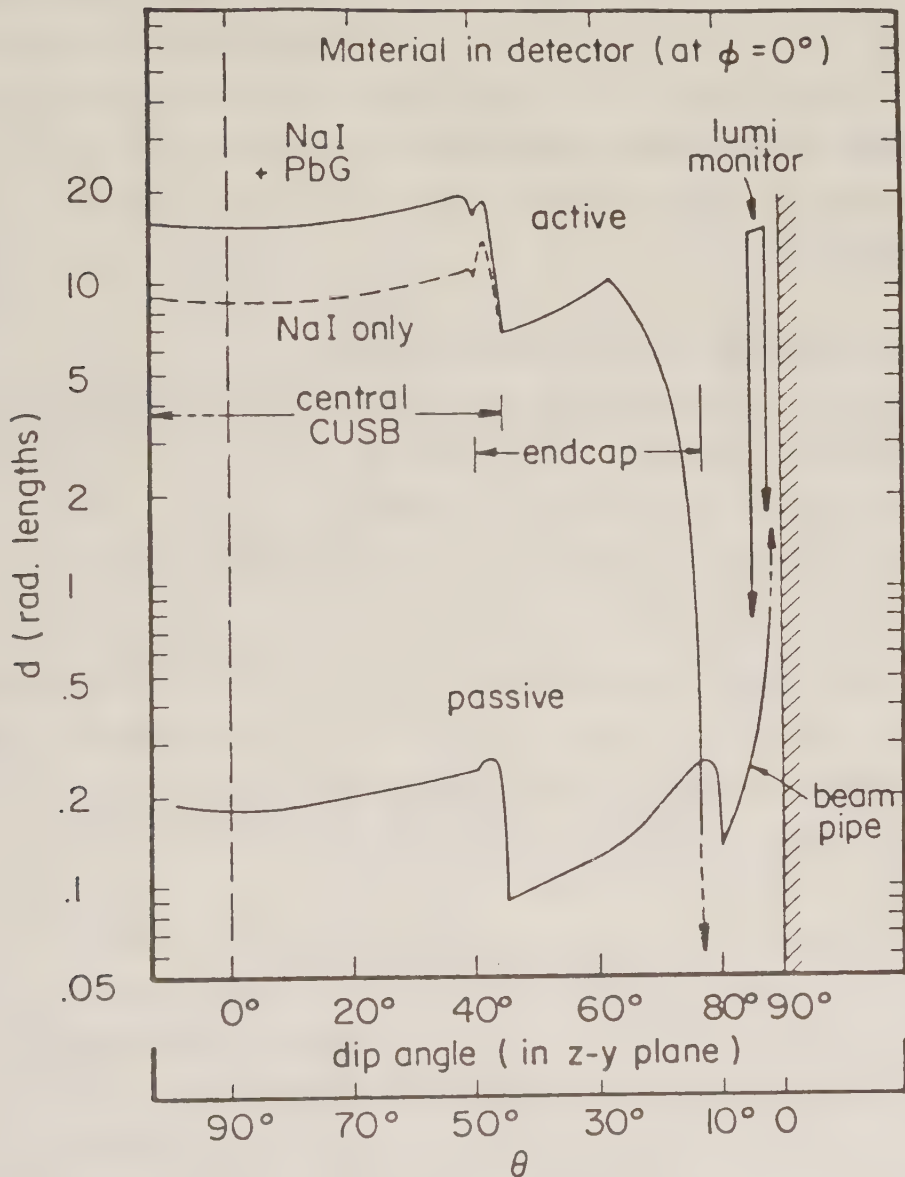


Fig. 3.13 The amount of active and inactive material of the CUSB detector in radiation lengths as a function of the polar angle θ .

In order to minimize the inactive material in the calorimeter, each thin (thick) crystal is cantilevered from the outer end towards the median plane by support bars made of 2 mm (3 mm) G-10 (a strong fiberglass material). The inactive material per NaI-plane which is listed in detail in table 3.4 corresponds to 1.1% (1.7%) of a r.l. for planes 1-4 (plane 5) at normal incidence. Fig. 3.13 shows the amount of active and inactive material in the entire calorimeter plotted in radiation lengths as a function of the polar angle θ .

Hamamatsu 9/8 inch phototubes (R 268) are attached to the thin crystals while RCA 3 inch tubes (4524) with a tea cup first dynode are attached to the thick crystals. To improve the light collection efficiency for the crystals in planes 3 and 4 two phototubes per crystal are used. All photomultipliers are followed immediately by preamplifiers which in turn feed the signals via ~5m coax cables into buffer amplifiers and ADC's (see III.3.2.1 and fig. 3.19).

III.2.2.2 The Lead Glass Cerenkov Counters (Pbc)

256 blocks of leadglass (SF5) with a thickness corresponding to 7 r.l. are arranged in 8x8 matrices. They back up the NaI to absorb any energy leaking out of the NaI from large electromagnetic showers. This arrangement allows a reasonably good energy resolution while maintaining a moderate cost for the calorimeter. In addition, the segmentation along the beam direction provides a measurement of the polar angle θ and therefore allows a reconstruction of space points for particles (e.g. for high energy photons) that penetrate the NaI. Table 3.5 shows for electromagnetic showers of different energies the percentage of particles penetrating into the Pbc and their average energy deposition in the Pbc, obtained from studies with the EGS Monte Carlo program (see chapter IV.2.2).

The lead glass array covers the same solid angle as the NaI. Each Pbc block has dimensions of $14.7 \times 14.7 \times 17.5 \text{ cm}^3$. The inactive material corresponds to 0.2% of a r.l. at normal incidence, which results from the wrapping of each block in a 0.1 mm thick aluminum foil and 0.2 mm light tight paper. Between lead glass blocks there is an additional 2.3 mm thick mu-metal foil. Light is collected by 5 inch RCA 7917 photomultipliers. The electronic readout of the Pbc blocks is analogous to the readout of the NaI crystals.

Table 3.5 Energy deposition of electromagnetic showers in the lead glass for different shower energies

E [MeV]	Events with energy in Pbc	Energy deposition in Pbc	Width (σ) of the energy distribution
100	49%	10%	8%
200	70%	9%	8%
400	94%	9%	7%
700	98%	11%	9%
5000	100%	18%	9%

Table 3.6a Geometric parameters of the outer strip chambers (OSC's)

Chamber	Sensitive Area [cm]	Distance to Beam [cm]
1	62.23 x 50.16	29
2	72.39 x 61.91	35
3	82.23 x 73.34	41
4	92.08 x 82.23	47

Table 3.6b Physical parameters of the OSC's

coverage ϕ :	2π with 5° gap at quadrant boundaries
θ :	$47^\circ - 133^\circ$
$\Delta\Omega/4\pi$:	60°
readout:	cathode readout in 2 planes
strip width:	1 cm strip plus 1 mm gap
gap width:	6.4 mm
anode wires:	gold plated tungsten, $\phi=20\mu$
wire spacing:	3 mm
operating HV:	1.9-2 kV
gas:	50% Ar and 50% ethane
gas gain:	$\sim 10^4$
ADC channels:	2280
efficiency:	100% for minimum ionizing particles and em showers with $E > 800$ MeV, $\sim 40\%$ for 100 MeV photons
resolution σ_x :	.45 cm, .6 cm, .75 cm parallel to sense wires for chambers 1 to 3.
σ_z :	.8 cm, 1.2 cm, 1.6 cm perpendicular to sense wires for chambers 1 to 3.
inactive material:	$\sim 2.4\%$ of a radiation length per chamber

III.2.2.3 Outer Strip Chambers

In the described arrangement the position and angular resolution of energy clusters in the NaI crystals and Pbc blocks alone is not very good especially for the direction along the beam. To improve the position and angular measurement for photons,⁺) outer strip chambers (OSC) are interleaved between all NaI layers, i.e. 4 chambers per quadrant with cathode strip readout both parallel and orthogonal to the beam direction. The OSC's vary in size from 62.23x50.16 cm² to 92.08x82.23 cm² thus covering the same solid angle as the NaI.

The construction of the OSC's is similar to that of the ISC's. The strip width is 10 mm, the gap between the cathode planes is 6.4 mm. The dead material per chamber (3.2 mm G-10, .1 mm Cu) corresponds to 2.4% of a r.l. at normal incidence, which is about a factor of 3 higher than for the ISC's. The relevant parameters for the OSC's are summarized in table 3.6.

A hybrid current preamplifier is directly attached to the end of each strip. The signals of all 2280 strips are sent via twisted pair cables into differential buffer amplifiers and into the ADC's. Due to a shortage of ADC channels only the 3 first planes of OSC's were read out following the installment of the ISC's.

For the cluster definition peaks and valleys in each plane above threshold are located. Starting from each peak all n adjacent strips on both sides with decreasing pulse heights are used to form a cluster. Here n is not restricted to values less than 4 because high energy electromagnetic showers (e.g. 5 GeV Bhabhas) can be very wide.

The pulse height difference between side and transverse view ranges from 15% to 20% depending on the chamber. Tracking is carried out in a similar way as for the ISC's. For photons with energies $E > 800$ MeV an accuracy in position measurement of typically $\sigma_z(\text{res}) \simeq 4.5$ mm ($\sigma_t(\text{res}) \simeq 8$ mm) for chamber 1 is obtained (for other chambers see table 3.6b) which results in an angular resolution of $\sim 1^\circ (\sim 2^\circ)$ for polar (aximuth) angles. For lower energy photons the angular resolution is worse. In addition, the efficiency to record a hit in the OSC's is only $\sim 40\%$ for 100 MeV photon showers and $\sim 70\%$ for 200 MeV photons. For high energy em showers (> 800 MeV) and energetic minimum ionizing particles, however, the efficiency is 100%.

⁺) For electrons and minimum ionizing particles a very good position and angular measurement is obtained from the ISC tracks.

Further details are described in [Hn 83].

For the running period at the T' resonance the OSC's were taken out to reduce the inactive material in the detector. This resulted in a ~21% improvement in energy resolution (from 7% to 5.8% for ~100 MeV photons, see IV.2), at the expense of poorer spatial resolution for photons.

III.2.3 Endcaps

Fig. 3.14 displays the endcaps (EC) in the two views. Each endcap consists of 84 NaI (Tl) crystals, arranged in a rectangular array of 10x10 crystals, with the central 16 elements removed for the beam pipe. Two sizes of crystals are used: $4 \times 4 \times 25$ cm³ for the outermost ring and $4 \times 4 \times 28$ cm³ for the other rings. Their long axis is oriented parallel to the beam direction. The crystals are bevelled at one side to match with the ISC's, as shown in fig. 3.14b. The total solid angle subtended by the EC's is 30% of 4π sr, covering 2π in the azimuthal angle ϕ without gaps, for the polar regions $18^\circ \leq \theta \leq 49^\circ$ and $131^\circ \leq \theta \leq 162^\circ$. There is an overlap with the CD at $\theta \sim 48^\circ$ and 132° . In the EC's the active material seen by a traversing particle ranges between ~7 r.l. (for $\theta = 45^\circ, \phi = 0$) and ~11 r.l. (for $\theta = 18^\circ, \phi = 45^\circ$). The radial segmentation of 3 layers allows a separation of electromagnetic showers from hadrons, which typically deposit energy only in one crystal in each ring, and background like beam-gas reactions, which deposit a large amount of energy only in the inner ring.

Each crystal is hermetically sealed with .1 mm aluminum foil and supported by a lightweight frame made of 1mm thick fiberglass. The entire amount of inactive material in the EC (without beam pipe) corresponds to 7.5%-11.5% of a r.l., depending on the incident angle. The light of each crystal is collected by a Hamamatsu 9/8 inch phototube (R 268). A preamplifier is directly attached to the tube base. The signal readout is done in the same way as for the CD crystals.

To separate charged from neutral particles a hodoscope, segmented into 16 azimuthal elements, is installed in front of the inner ring (ϕ hodoscope). Each scintillator is bent around the end of the NaI crystals (see fig. 3.14b) to be sensitive to polar angles $\sim 45^\circ$ thus covering the same solid angle as subtended by the EC crystals. To obtain polar angle information for a developing shower in the EC, 4 hodoscopes consisting of 4 elements each with roughly equal segmentation in $\cos\theta$ are installed between the inner and middle ring (θ -hodoscope).

Each θ hodoscope is composed of a scintillator (NE 104B), a BBQ wave length shifting bar, a light pipe, and a Hamamatsu 3/8 inch photomultiplier (R 647). This yields a very compact package with very little dead space.

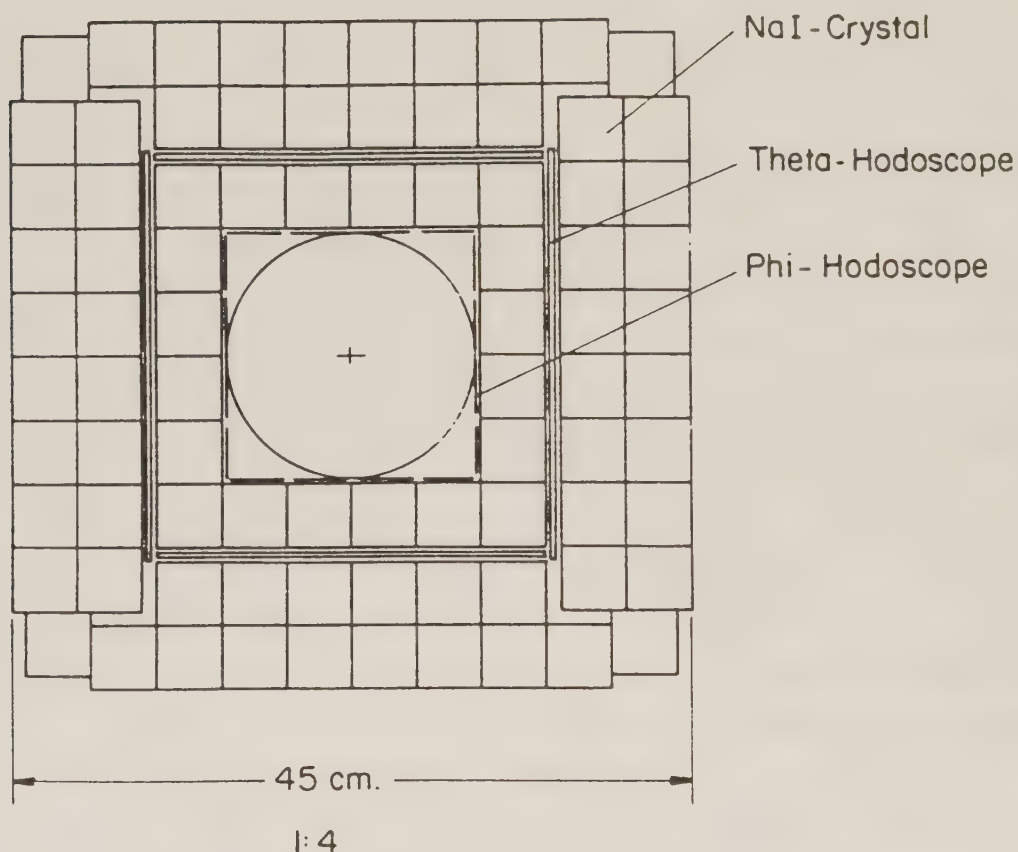


Fig. 3.14a Transverse view of the endcaps.

III.2.4 Muon Counters

Following the quadrant configuration of the CD, plastic scintillator counters for muon detection are installed behind the Pbc. They are used for triggering on back-to-back muon pairs. The initial arrangement consisted of 27 counters covering 32% of the total solid angle. For the $\mathbf{T}'$ running period the solid angle coverage was increased to 42.6% of 4π sr, by

- moving top and bottom counters 10cm closer to the interaction point.
- installing 8 new counters to cover most of the gaps at quadrant boundaries.

1:4

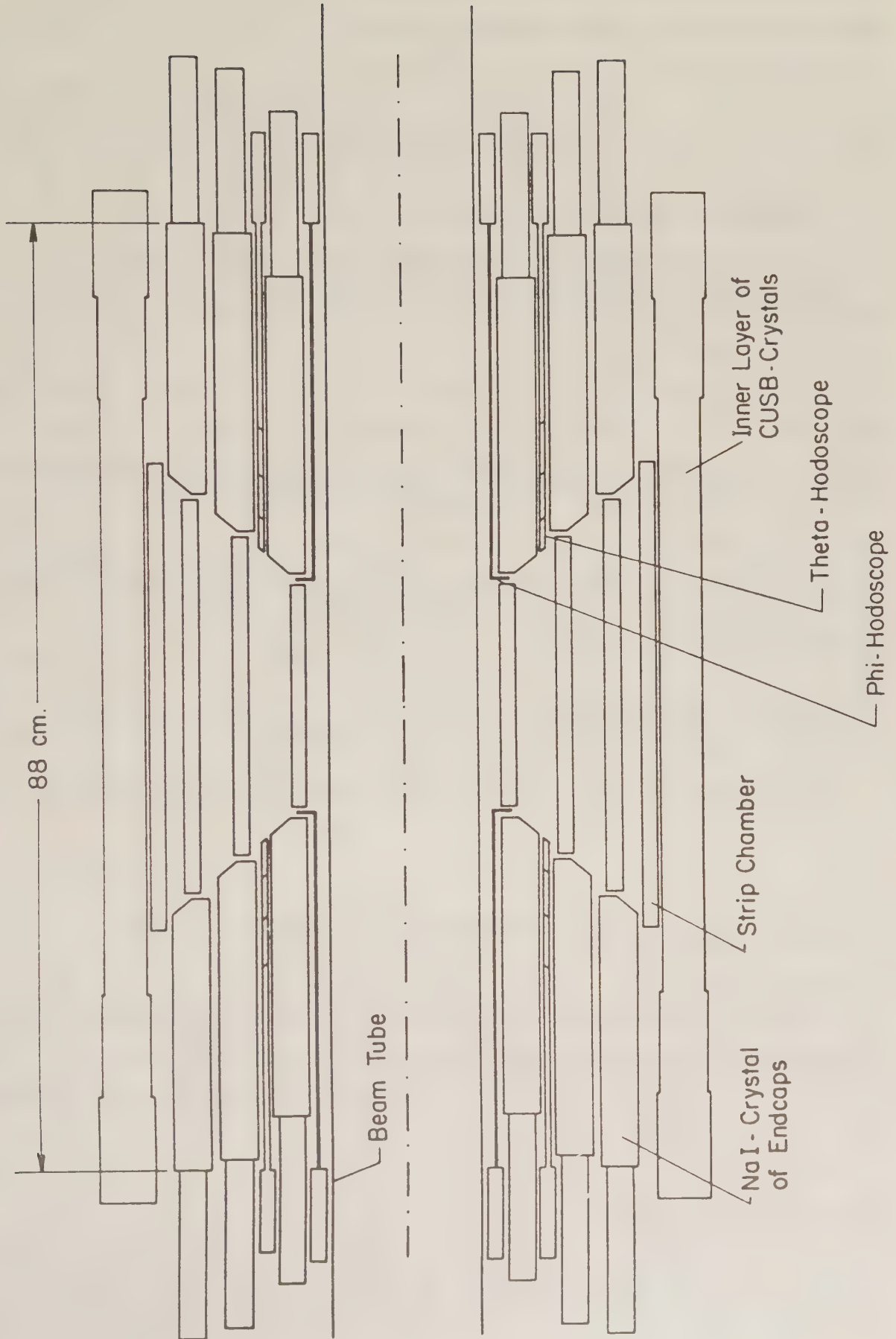


Fig. 3.14b Side view of the endcaps, showing the perfect match with the ISC detector.

Table 3.7a Geometric properties and acceptance of muon trigger counters

	Dimensions of counters	coverage ϕ δ	
10 old counters at top:	25 x 140cm ²	62°	28.5°
9 old counters at bottom:	25 x 140cm ²	60°	30°
4 old counters at south and north:	33 x 130cm ²	62°	31°
4 new counters at edges in north-south:	40 x 140cm ²	55°	32°
4 new counters at edges in top-bottom:	20 x 140cm ²	24°	29°

Table 3.7b Angular coverage of muon trigger counters in their present and previous state. The numbers are in percent of 4π .

SETUP	Ang. Dist.	Total	T/B	S/N
old (Dec 81-Dec 82)	isotropic	32	14	18
	$1+\cos^2\theta$	25	11	14
new (since Dec 82)	isotropic	42.6	18.8	23.8
	$1+\cos^2\theta$	34.3	15.0	19.3

The old setup was used in the T'' running period, the new setup in the T' running period.

Table 3.8 Acceptance and efficiencies for triggering on μ pairs

SETUP	Model	≥ 1 Hit	2 Hits	Accepted	Lost
old (Dec81-Dec82)	isotrop	31.7	29.0	28.3	0.7
	$1+\cos^2\theta$	26.3	23.7	23.3	0.4
	3S $\rightarrow$ 2S	27.1	23.5	22.3	1.2
	3S $\rightarrow$ 1S	29.3	21.6	18.1	3.5
	2S $\rightarrow$ 1S	27.9	22.8	20.8	2.0
new (since Dec82)	isotrop	43.0	41.2	39.2	2.0
	$1+\cos^2\theta$	34.9	33.4	31.4	2.0
	3S $\rightarrow$ 2S	36.3	33.1	30.8	2.2
	3S $\rightarrow$ 1S	39.1	30.4	25.2	5.2
	2S $\rightarrow$ 1S	37.4	32.0	28.8	3.2

Tables 3.7a,b summarize the geometric parameters and acceptance of all counters in detail. The scintillators (NE110) have a light attenuation of about a factor 2 over the total length. The scintillation counters are viewed by fast photomultipliers (RCA or Philips XP2020). The PM bases have a built in discriminator to provide a fast digital pulse for triggering and timing purposes in addition to the analog signal.

To set up a trigger the counters are connected in a 'staggered OR', i.e. all combinations of two adjacent counters on one side and one counter diametrically opposite, collinear with the interaction point, are connected in coincidence. This method allows one to compensate for a slight misalignment in the counters and for some acollinearity between the muons. For example in the transition $\Upsilon'' \rightarrow \gamma\gamma\Upsilon \rightarrow \gamma\gamma\mu\mu$ the maximum acollinearity is 11° . Table 3.8 summarizes acceptances and efficiencies for muon pairs from the transitions $3S \rightarrow 2S$, $3S \rightarrow 1S$, and $2S \rightarrow 1S$ in the previous and present arrangement, as obtained from MC studies.

Because the total material in the CD is not sufficient to stop all charged particles, the collinearity requirement of the muon trigger is needed to reduce background from hadronic events. The background from cosmic muons is rather small. The rate in the north area enclosure is only .02 Hz. However, due to a finer segmentation of the top-bottom counters, the trigger logic and the small gate width of 30 ns for the time-of-flight system, the rate is reduced to 2×10^{-4} Hz. In comparison the total trigger rate for the detector is ~ 1 Hz.

III.2.5 Muon Filters

Two large iron toroids have been installed for muon identification, backing up the south and north quadrant of the central detector.⁺⁾ The side view for the south side is shown in fig. 3.15. Location and size are determined by the physical constraints in the north area enclosure, i.e. size of the pit and position of the synchrotron beam pipe. This leads to a coverage in solid angle of only 25% of 4π sr.

⁺⁾ The main purpose of the muon filter is to study both events with multileptons (e.g. $\mu\mu^-$, $e\mu$ -pairs) and processes with a single muon in the final state (such as the semileptonic B-meson decay on the Υ''' peak). In the present analysis, however, the muon filters are only used to check our criteria for muon to hadron separation.

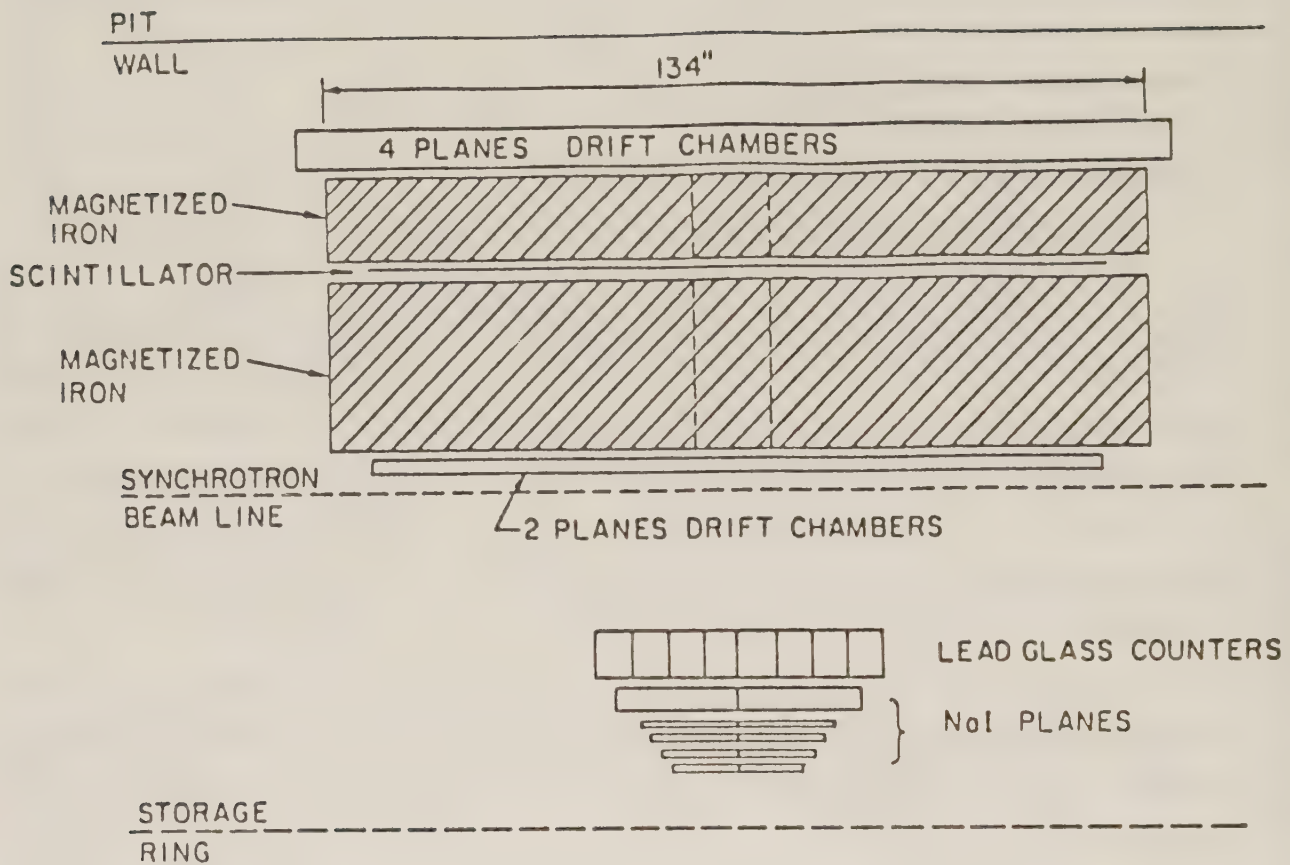


Fig. 3.15 Side view of the muon filter (south side).

The iron can be magnetized up to 1.5 Telsa. However, for the data presented here the magnetic field was turned off.

Particle tracking and momentum analysis is accomplished with 35 drift chambers (DC) for each arm, arranged in 6 planes, 3 vertical and 3 horizontal. Two planes (one of each) are located in front of the iron to determine, in conjunction with the ISC track information, the ingoing trajectory, while 4 planes (2 of each) behind the iron measure the direction of outgoing particles. A total of 408 sense wires are read out. The preamplifiers are directly mounted to the chambers. After discrimination the pulses of each wire stop a time-to-digital converter (TDC), which is started by the beam crossing pickoff signal. The position resolution is $\sigma=3$ mm per plane. Further details are described in [PAC 82, PAC 83].

To provide a trigger for single and dimuon events in addition to the muon counter trigger, a segmented plane of 7 scintillators in each arm is positioned after 67cm of iron. It requires a hit in the scintillator of the muon filter, along with a hit in one of the counters of the dimuon trigger, and a minimum ionizing pattern in the central detector, all on the same side of the detector.

III.2.6 Luminosity Monitors

The luminosity monitors are positioned 1m upstream of the interaction region on both sides. As schematically shown in fig. 3.16, each luminosity monitor is divided into 4 sectors mounted around the beam pipe, each containing a compact arrangement of 2 scintillation counters (10mm thick NE 110) and a 44 layer lead-scintillator sandwich calorimeter, corresponding to 15r.l., with BBQ-wavelength shifter bar readout.

The monitors cover an azimuthal region of 61% of 2π in the polar region $45^\circ \leq \theta \leq 90^\circ$ mrad, leaving space for two vacuum pumps. Table 3.9 summarizes the geometric parameters of each sector.

Table 3.9 Geometric properties of luminosity counters

Counter	Z [cm]	θ_{in} [mrad]	θ_{out} [mrad]	ϕ
A	160	47	84	45°
B	161	43	86	50°
Calorimeter	<166>	39	90	55°

The luminosity monitors detect small angle Bhabha scattering. A luminosity count requires a coincidence between two sectors diagonally opposite to the interaction point. In addition, each sector must register a hit in both counters and deposit sufficient energy (>3 GeV) in the calorimeter to reject accidental coincidences or beam gas interactions.

The light of each scintillator and of each lead scintillator sandwich is collected by photomultipliers. The output signal of each photomultiplier is passively split 2:1:1 with:

- a) 50% to discriminators
- b) 25% to ADC's for pulse height recording
- c) 25% for monitoring.

During a 12 month operation the signals from the lead scintillator sandwich calorimeter decreased by 30%. The exact reason was unclear, but it may be due either to radiation damage or a loss of light transmission. The loss was adjusted by increasing the HV for the photomultipliers by 10%.

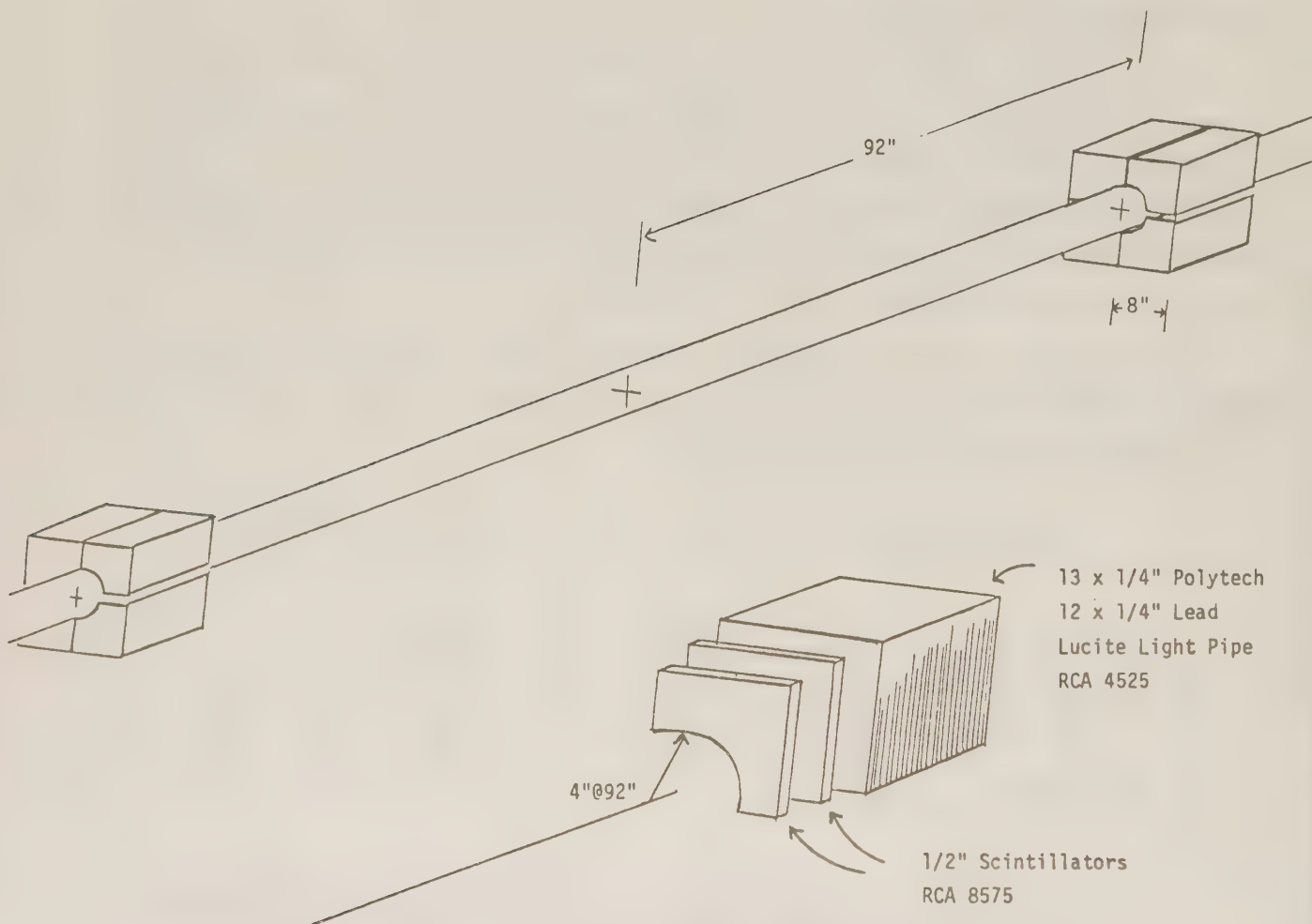


Fig. 3.16 Schematic drawing of the luminosity monitors, in situ and in an exploded view.

To determine the luminosity, the number of luminosity counts is divided by the Bhabha cross section, adjusted for radiative corrections and integrated over the fiducial volume of the luminosity monitors. However, the systematic uncertainties using small angle Bhabha's are large:

- i) The Bhabha cross section becomes very large at small angles, diverging for $\theta \rightarrow 0$. This places stringent demands on the accuracy for the position of the luminosity monitors. In addition each electron has to pass ~ 3 cm of aluminum beam pipe resulting in losses due to a large scattering probability.
- ii) Radiative corrections become large at small angles so that second order effects have to be included.

On the other hand the CD is a perfect Bhabha counter, identifying a 5 GeV electron unambiguously with $\sim 100\%$ efficiency (in $>15r.l.$). The counting rate for large angle Bhabhas scattering is reasonable due to the 60% coverage of the total solid angle, and systematic uncertainties are small. Thus, for normalization of other cross sections and branching ratios we use the integrated luminosity as determined from large angle Bhabha scattering.

III.3 Electronic Setup

III.3.1 Trigger

The trigger is essentially a minimum energy requirement in coincidence with a bunch crossing.⁺⁾ The system has 5 different types of triggers interconnected in an 'OR' mode:

- i) a total energy trigger, requiring an energy deposition of more than 1 GeV in the three outer planes of the CD NaI crystals (see fig. 3.20).
- ii) a distributed energy trigger, requiring that the event deposits ≥ 700 MeV in the CD distributed at least among 3 octants, each containing ≥ 100 MeV in the last four planes, and one octant in the opposite polar half, as shown in fig. 3.20.
- iii) an endcap Bhabha trigger, requiring an energy deposition of more than 1 GeV in each EC together with an energy deposition ≥ 50 MeV in the CD.
- iv) a single muon trigger, as described in section III.2.5.
- v) a dimuon trigger, as described in section III.2.4.

The total energy trigger contains all Bhabha-like events and most of the hadronic events. The distributed energy trigger also selects hadronic events (for example 3 jet-like events where a large amount of energy is lost or deposited in the EC's) while suppressing beam-gas and beam-wall interactions.

⁺⁾ The 'bunch crossing' signal is obtained from an electrode, located inside the beam pipe about 3 m from either side of the interaction region. A passing bunch induces a signal on the electrode.

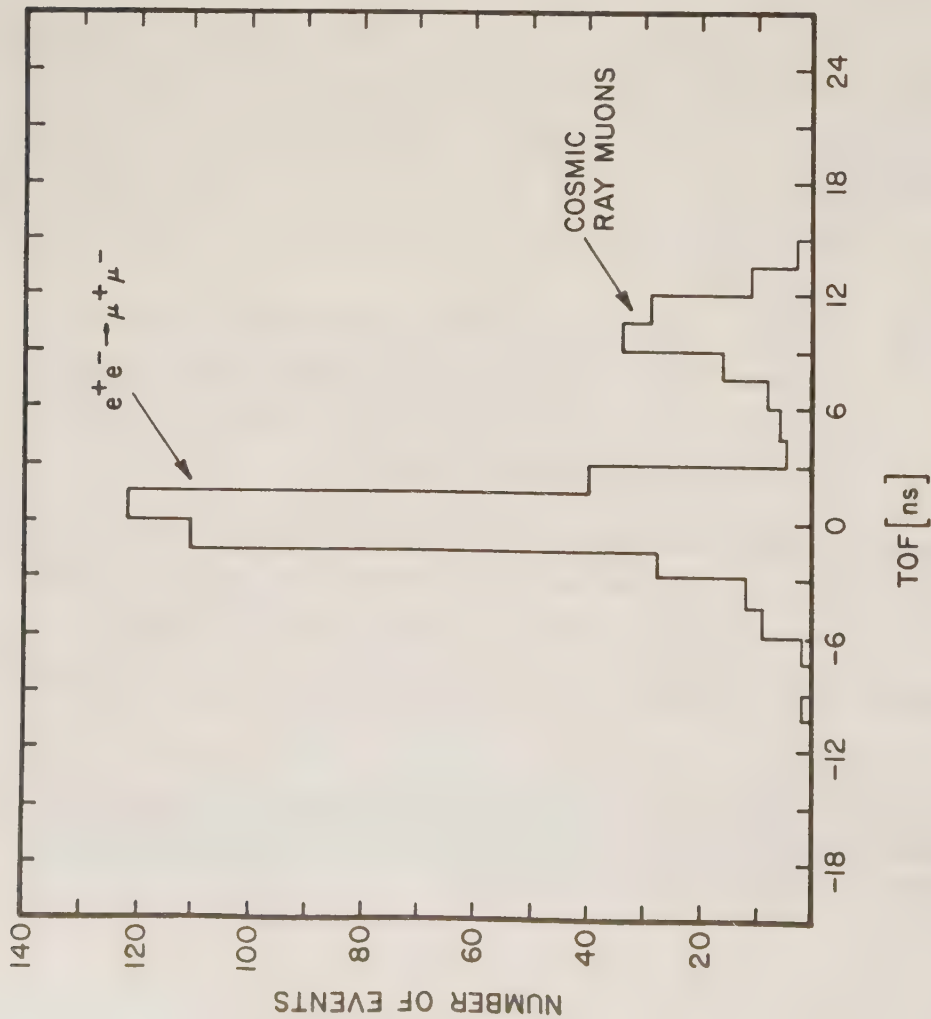


Fig. 3.17 Time of flight spectrum for dimuon triggers passing through top-bottom muon counters.

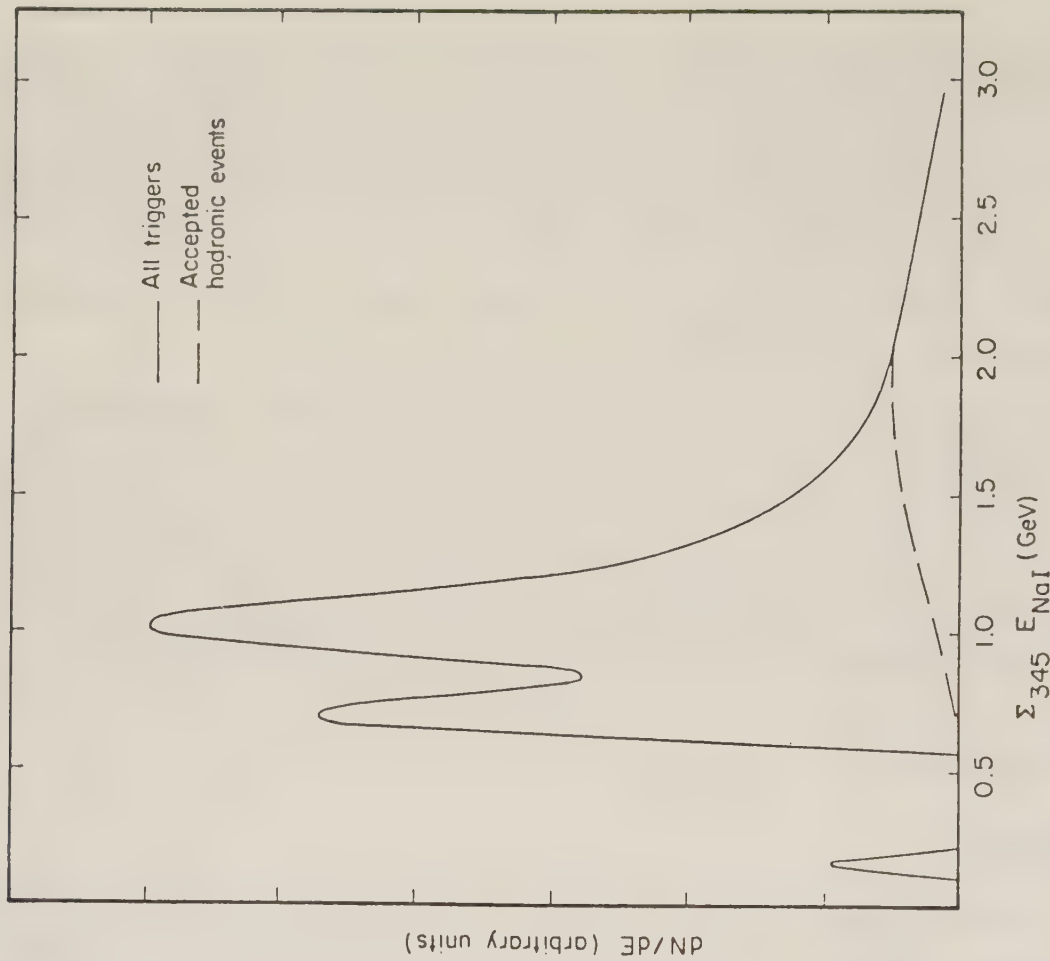


Fig. 3.18 Distribution of different triggers in the central detector vs. the summed energy in the outer three planes of the NaI. The three peaks result in order of increasing energy from the dimuon trigger, the distributed energy trigger and the total energy trigger. The dashed line indicates the energy spectrum for triggers passing the hadronic event

The additional 50 MeV requirement in the EC-Bhabha trigger allows a moderate trigger rate without losing events of interest (such as $e\bar{e}\gamma\gamma$ events with at least one photon in the CD). The cosmic ray background in the single and dimuon trigger is small, since:

- i) The gate width (started by the beam crossing signal) which defines the coincidence is only 30 ns (60 ns) for the dimuon (single muon) trigger.
- ii) The experiment is located ~15 m below ground level.

Therefore, the fraction of cosmic ray muons is negligibly small in events traversing the north or south quadrants of the detector, i.e. in all single muon triggers and in about half of the dimuon triggers. For dimuon triggers in the top-bottom quadrants, however, the cosmic ray muons can be nearly entirely separated from 2 muon decays of the Υ -states or the continuum by analyzing the time-of-flight spectrum. Fig. 3.17 shows as an example the time-of-flight spectrum for dimuon events from Υ decays. Two distinct peaks separated by ~10 ns are visible. Cutting in the TOF spectrum at 5 ns therefore allows one to eliminate nearly all cosmic ray muons.

The coincidence time for the first three triggers is set to 300ns. For a luminosity of $10^{31}\text{cm}^{-2}\text{s}^{-1}$ at the Υ the total trigger rate is approximately 0.3 Hz. Fig. 3.18 shows the distribution of energy deposited in the outer three NaI planes for all accepted triggers. The three peaks come in order of increasing energy from the dimuon trigger, the distributed energy trigger and the total energy trigger.

III.3.2 Data Acquisition System

The data acquisition system consists of:

- a) a 4096 channel ADC system to record the analog pulse heights of the NaI crystals, Pbc blocks, ISC's, OSC's and the different hodoscopes.
- b) a 440 channel TDC system for time digitization of the muon drift chambers and the muon time-of-flight counters.
- c) a set of 12 bit coincidence registers to record event specific information like trigger type, event type (hardware defined), partial energy sums, hit patterns in the scintillators of the 2-muon counters and muon filters, and flags for high voltage trips of the strip chambers.
- d) a set of scalars recording specific run quantities like running time, gated and ungated luminosity counts, integrated luminosity, total triggers, bad beam interactions, number of different event types etc.
- e) a transfer line to the CESR control room sending auxiliary information such as beam currents, NMR currents and the corresponding beam energy.

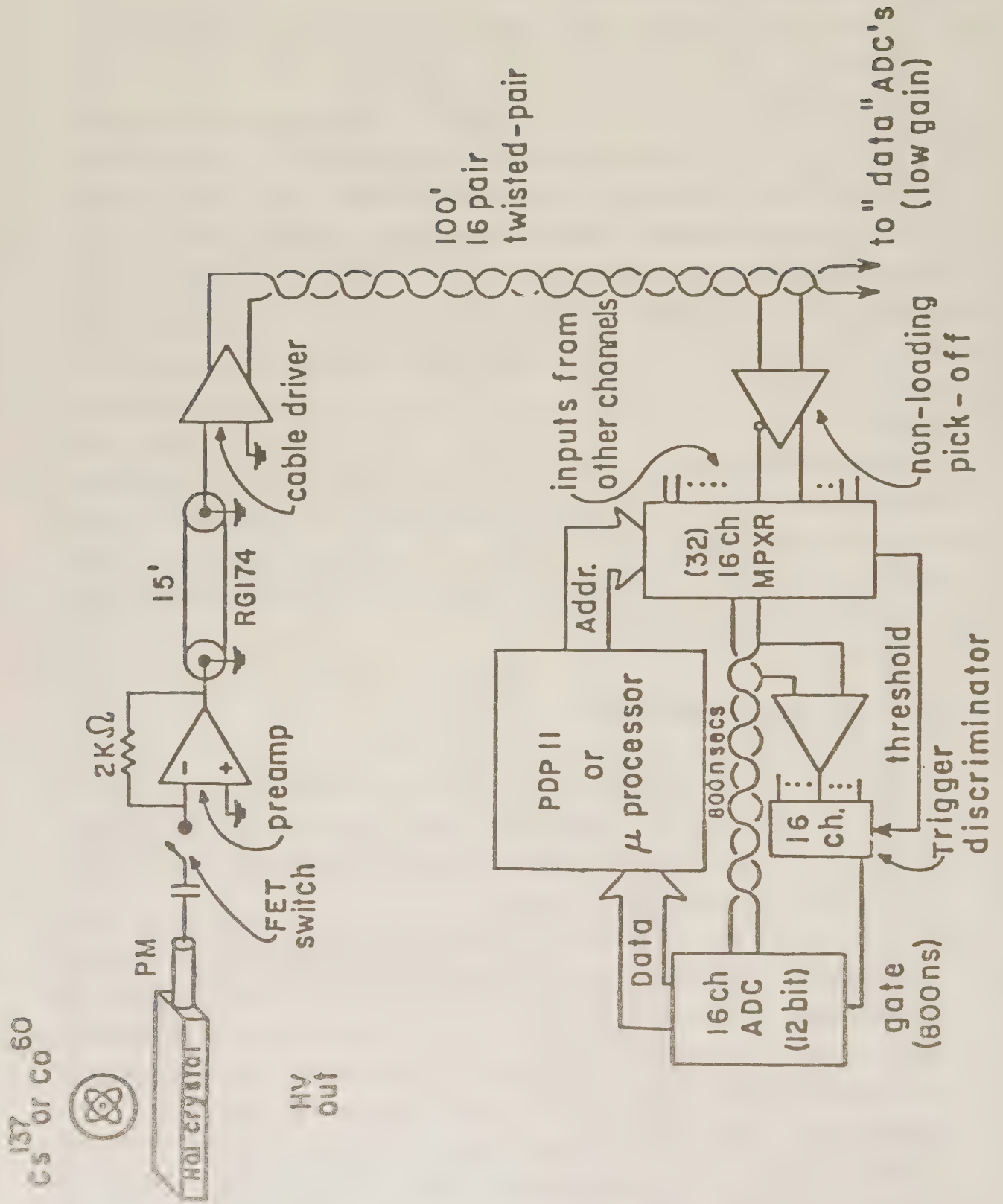


Fig. 3.19 Schematics of the signal readout and source calibration of the NaI crystals

For every trigger all ADC's, TDC's, coincidence registers and the information from the control room are read out, whereas scalars are read out only every 30 min.

In the present analysis the TDC information plays a minor role, because we only use the muon filter to check our muon criteria. Therefore we refer to [Ms 83] for a detailed discussion of the TDC system. On the other hand, the ADC system is used to measure particle energies and to perform an online calibration system and is therefore discussed in more detail.

III.3.2.1 NaI Crystal Readout

Fig. 3.19 shows schematically the signal readout of the NaI crystals. The amplified signal from a photomultiplier is transmitted via 100 Ω twisted pair cables to the data ADC's. To determine the energy deposited in each crystal or Pbc block for triggering and calibration purposes the signal is tapped by a high impedance pickoff amplifier. The pickoff amplifiers are connected to an energy calibration system consisting of a higher gain ADC system. During data taking this records the pulses of radioactive sources mounted on each crystal (see III.3.4). Linear summed outputs are generated for groups of 4, 8, or 16 channels as shown in fig. 3.20. In successive steps the summed outputs of layers, octants and quadrants of the CD are formed. For the energy deposition in the EC's, analog sums of each EC are produced both for rings of layers and quadrants. The analog sums are connected to discriminators where the desired logical functions which constitute the trigger are generated.

III.3.2.2 The ADC System

The ADC's were designed and built at Nevis Labs. They are 12-bit charge sensitive units with true differential input for high common mode rejection. The peak sensitivity is 150 pcoul for strip chamber signals, 300 pcoul for Pbc signals, and 500 (1000) pcoul for signals from the CD (EC) NaI crystals. The differential non-linearity is 0.1%.

The amplifier gains for the calorimeter cells are adjusted to measure a 5 GeV electron shower without saturation. The individual energy scales for NaI crystals and Pbc counters are summarized in detail in table 3.10. The energy scale of the strip chamber ADC's is chosen such that the minimum ionizing peak corresponds to $\sim 1/10$ ($\sim 1/20$) of the full range for the ISC's (OSC's).

ENERGY TRIGGER HARDWARE

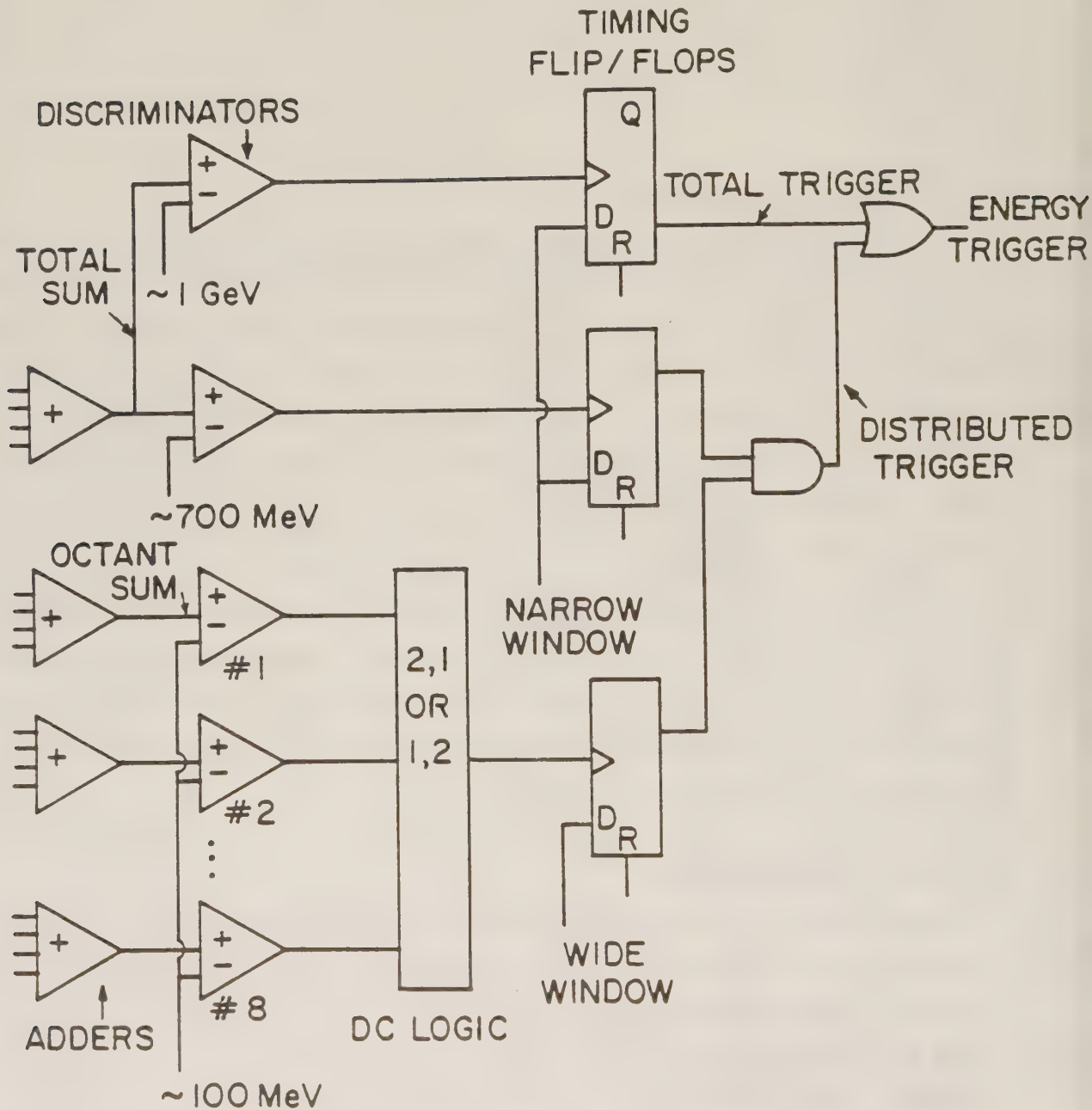


Fig. 3.20 Main elements of the trigger hardware.

For each beam crossing (every $2.56\mu\text{s}$) all ADC gates are opened. To accomodate the different pulse shapes the gate widths are set to 800ns for NaI signals (to accomodate the long decay time of NaI), 500ns for Pbc signals and 300ns for strip chamber pulses. If no trigger is present all ADC's are reset by a fast clear to be ready for the next beam crossing. In case of a trigger a command is sent by the online computer to read out all ADC's.

Since the ADC's are AC coupled the pedestals are nearly independent of the integration time. They result essentially from the charge injection caused by closing the analog switch to hold the integrated charge. The pedestal distributions peak typically around channel number 320 (250) for NaI and Pbc (strip chamber) ADC's with widths of $\Gamma=8$ (12) counts. The noise broadening is of the order of $\Gamma=1-2$ channels. The pedestals tend to drift over long running times. To compensate for drift, pedestals are recorded at the beginning of every run with the preamplifiers turned off. To update the pedestal files used for the data analysis new pedestal distributions are generated offline every few runs.

Table 3.10 ADC energy scale for NaI crystals and Pbc blocks

ADC's for	Full Energy Scale
NaI, layers 1-2	0.55 GeV
NaI, layers 3-4	1.1 GeV
NaI, layer 5	2.5 GeV
EC NaI	1.5 GeV
Pbc	2.0 GeV

III.3.2.3 Data Transport

The data acquisition is controlled by a PDP 11/20 online computer. The set up, schematically shown in fig. 3.21, is based on two important criteria:

- i) The system should be able to transfer a large amount of data to magnetic tape while incurring a low dead time.
- ii) The system should be flexible enough to accomodate changing experimental conditions without major changes (e.g. including more ADC, TDC, or scalar channels).

DATA ACQUISITION SYSTEM

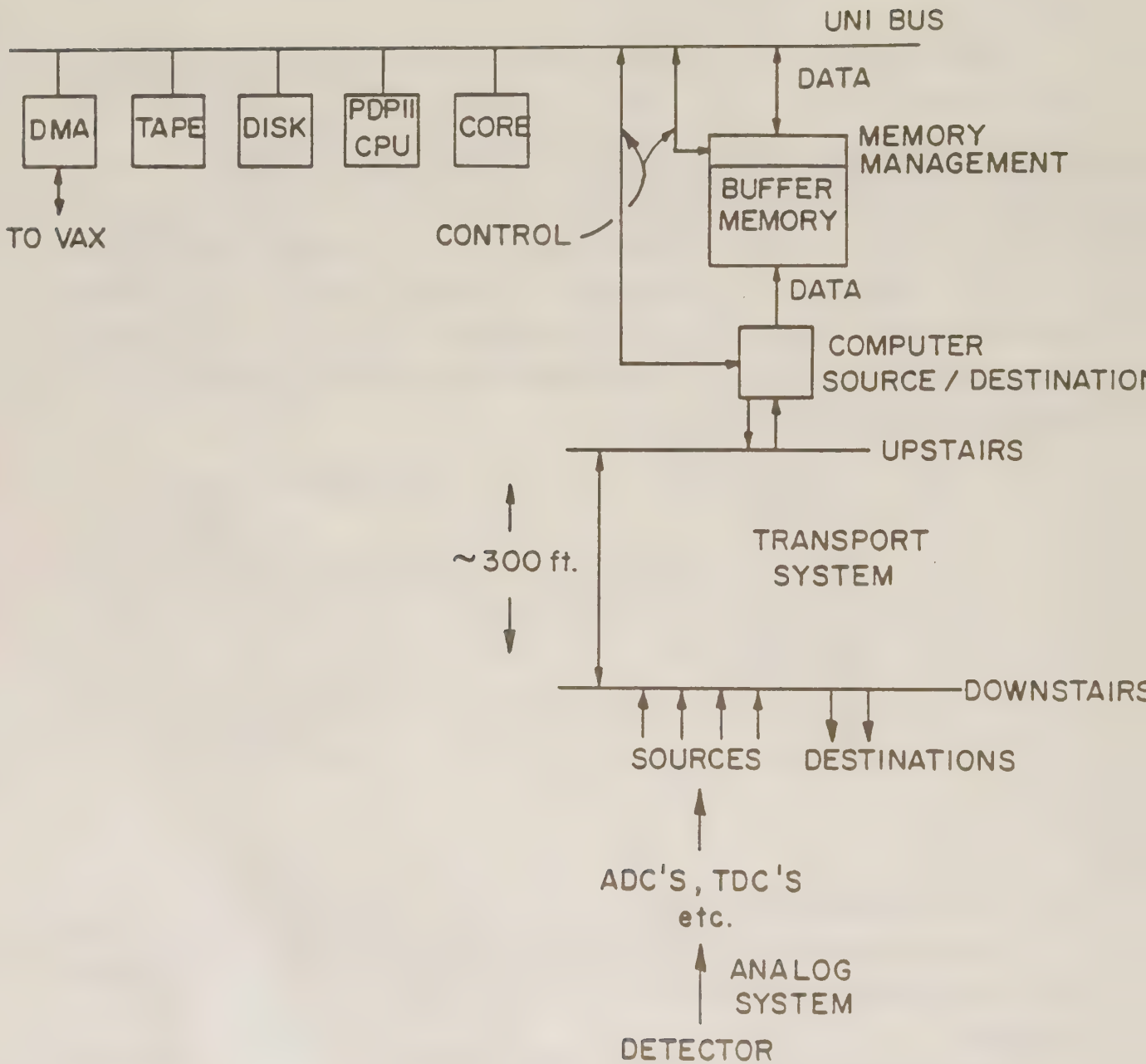


Fig. 3.21 Schematic drawing of the data acquisition system, showing in particular the transport system.

The central part of the data acquisition hardware is the so-called transport system which connects two busses -- a bus in the fast electronics room with a bus ~100m away in the computing room ⁺) -- via a high speed bi-directional data path (200 ns per 16-bit word). The electronics room bus contains electronics boards, or 'sources', each corresponding to a different readout component (ADC, TDC, coincidence register and scalars). The sources transmit ~4000 16-bit words per trigger to a 'destination' board in the computing room bus. The destination board in turn relays the data to the computer on command. To accomodate a high transmission rate and maintain a low dead time the transport system is linked to a 32k-byte dual port buffer memory (capacity for ~7 events) where events are stored until they can be processed by the online filtering program (see next paragraph). The total dead time of the data transport system is 5ms per event (4ms memory-limited time plus 1ms for the PDP CPU). Combined with a trigger rate ranging between .1 and .5Hz this results in a >99.5% live time for the system.

The online PDP 11 also has a bidirectional link to a VAX 11/780 where an online filtering program is run. An event is only written to magnetic tape if it passes the criteria of the software filter discussed in the next section. Also an online monitoring program is run on the VAX, which displays triggers on a television monitor and accumulates histograms of signals from the different detector components. The VAX also controls a second PDP 11/20 computer which is used solely for calibrating the NaI crystals during data taking. Further details of the data acquisition system are discussed in [Ri 83, Sp 83].

III.3.3 Software Filter

The purpose of the software filter is to select all events of interest originating from e^+e^- interactions (e.g. Bhabhas scatters, hadron jets, lepton pairs etc.) while reducing the background from beam-gas and beam-wall interactions. The selection criteria are based on energy deposition in the NaI crystals and Pbc counters in the CD. In the following we just list the individual criteria for completeness without further explanation. A detailed discussion can be found in [Sp 83, Ri 83].

⁺) The electronics room is located in a separate tunnel near the experiment ~15 m below ground level, whereas the online computer is in a trailer at ground level.

First a few definitions are necessary:

- 1) Hit crystal: Any crystal in planes 1 to 4 with energy $E_i \geq 10$ MeV or in plane 5 with $E_i \geq 21$ MeV.
- 2) Hit sector: A sector containing 3 or more hit crystals.
- 3) 'Edge sector': (a somewhat misleading nomenclature) A hit sector having adjacent sectors on both sides with essentially no energy deposition, i.e. it satisfies one of the following conditions:
 - i) $E_i(\text{adjacent sector}) < 1/5 E_i(\text{hit sector})$ for $i=1-4$
 AND

$$\sum_{i=1}^4 E_i(\text{adjacent sector}) < 1/10 \sum_{i=1}^4 E_i(\text{hit sector})$$
 - ii) $E_i(\text{adjacent sector}) < 5$ MeV for $i=1, 4$
 AND

$$\sum_{i=1}^4 E_i(\text{adjacent sector}) < 10$$
 MeV
- 4) Minimum ionizing track: A hit sector with a regular energy pattern of 10-25 MeV in planes 1 to 4 and 40-80 MeV in plane 5.
- 5) CD-track: A CD track requires at least 4 crystals in one sector with energy $E_i \geq 7$ MeV and $\sum_i E_i \geq 40$ MeV.
- 6) E_{oct} : Total NaI energy in one octant.
- 7) E_W (E_E): Total NaI energy in the polar west (east) half.
- 8) E_{NaI} : Total NaI energy in the CD.

Event Selection Criteria

Any event that satisfies one of the following conditions is stored on magnetic tape:

- 1) ≥ 1 octant with $E_{\text{oct}} > 1.5$ GeV AND ≥ 1 edge sector with hits in plane 2-5.
- 2) ≥ 1 octant with $E_{\text{oct}} > 1$ GeV AND ≥ 1 edge sector with hits in planes 1-5.
- 3) 1 octant with $E_{\text{oct}} > 600$ MeV AND all other (7) octants with energies $E_{\text{oct}} < 50$ MeV.
- 4) 2 opposite quadrants, each containing an octant with $E_{\text{oct}} > 600$ MeV AND ≥ 2 edge sectors with hits in planes 2-5
- 5) ≥ 3 sectors with hits in planes 2-4 or 1-3, being separated by ≥ 3 sectors from each other AND ≥ 2 sectors with hits in plane 1-5, separated by ≥ 2 sectors AND ≥ 2 'edge sectors' with hits in planes 2-5 AND $E_{\text{NaI}} > 1$ GeV.
- 6) the large angle Bhabha selection criteria.
- 7) any of several hadronic selection criteria.
- 8) the μ -pair selection criteria.
- 9) all EC triggers.

For large angle Bhabha selection we use two different criteria which have an overlap of 95%. One criteria requires two nearly collinear electromagnetic (em) showers with energies >1 GeV and containing at least 90% of the total energy observed in the CD. The other criteria essentially requires events with a high 'thrust' value of $T > .99$ (see section IV.2.6 for definition of thrust). For details of the large angle Bhabha criteria see [Sp 83].

For the hadronic event selection several criteria exist which are discussed in detail in [Ri 83]. The one which is most efficient and therefore used for normalization purposes in this thesis basically requires at least three CD-tracks.

To select μ -pairs we require at least one minimum ionizing track in conjunction with $E_{\text{NaI}} \leq 1.5$ GeV.

Bhabha, hadronic, and μ -pair events are labelled by characteristic flags which are used to locate these events in the offline analysis.

III.4 Energy Calibration

The gain of the photomultipliers for the NaI and leadglass counters drift with time. The main cause for drifts is long exposure to high data rates⁺). Therefore it is necessary to have a calibration and drift monitoring system which runs simultaneously with data taking. To accomplish the energy calibration for the NaI crystals in the CD and EC's radioactive sources are permanently attached to each crystal. For the EC and thick CD crystals of plane 5 ^{60}Co sources are used which emit two monochromatic gammas of 1.17 and 1.37 MeV. Since both photons are emitted almost coincidentally the energy sum line of 2.5 MeV is also used. Due to the large solid angle the acceptance for observing both γ 's in one crystal is $\sim 30\%$. For the thin crystals in planes 1 to 4 ^{137}Cs is used which emits a monochromatic photon of .662 MeV.

In order to monitor the photomultiplier gains of the NaI crystals the signals are branched off from the ADC signal lines (compare fig. 3.19). The very small signals are amplified by a factor ~ 100 , then connected via an analog multiplexer to an additional amplifier and discriminator board and fed in groups of 16 with 100ns delay into reference ADC's. The

⁺) Especially after a period of machine studies the gains increased by several percent.

discriminator signal is used to open the ADC gate. The ADC's are read out by a dedicated PDP 11/20.

For each crystal a pulse height distribution of the source signal is generated from 500 events. The distributions are fitted and the calibration constants are automatically updated. It takes about 5 hours (corresponding to ~two runs) to calibrate all 500 NaI crystals. Absolute cross calibration of the reference ADC's and the data ADC's is achieved with a precision pulser producing the same pulse shape as from NaI signals.

The Pbc counters have been calibrated in several steps. First four complete sectors of the CD (NaI-Pbc plus strip chambers) were assembled in the Brookhaven AGS test beam [Sp 83]. The energy calibration of the Pbc was achieved using .5, 1, 2, and 4 GeV electrons. Once the energy calibration was obtained the energy deposited by minimum ionizing pions in the Pbc could then be determined. To facilitate calibration of the Pbc in the final installation, ^{241}Am sources embedded in NaI chips were used to calibrate LED's attached to each Pb block. The ^{241}Am sources had been previously calibrated by using cosmic ray muons. About once a day the LED's were pulsed to check the Pbc calibration and drift. For details see [Sz 83].

The overall calibration of the NaI-Pbc array is cross-checked by electrons from Bhabha scatters. From a study of the dependence of the total shower energy versus the fraction of energy deposited in the Pbc, the lead glass calibration relative to the NaI calibration can be adjusted. This results in a readjustment of the Pbc source calibration downward by 10% to 20% depending on the quadrant. To obtain the absolute energy scale for Bhabha scatters one has to correct for losses in the inactive materials and leakage out of the calorimeter. This results in a second correction of both the NaI source calibration and the adjusted Pbc calibration upward by 20% to 25% again depending on the quadrant.

Fig. 3.22 shows the energy distribution for 5 GeV electrons obtained by this procedure. The resolution is 5.8% FWHM. The calibration and stability for each NaI crystal and Pbc block is also cross-checked by analyzing minimum ionizing particles from hadronic events and cosmic ray muons, depositing typically 15 MeV in the thin NaI crystals, 60 MeV in the thick NaI crystals and 200 MeV in the Pbc blocks, respectively.

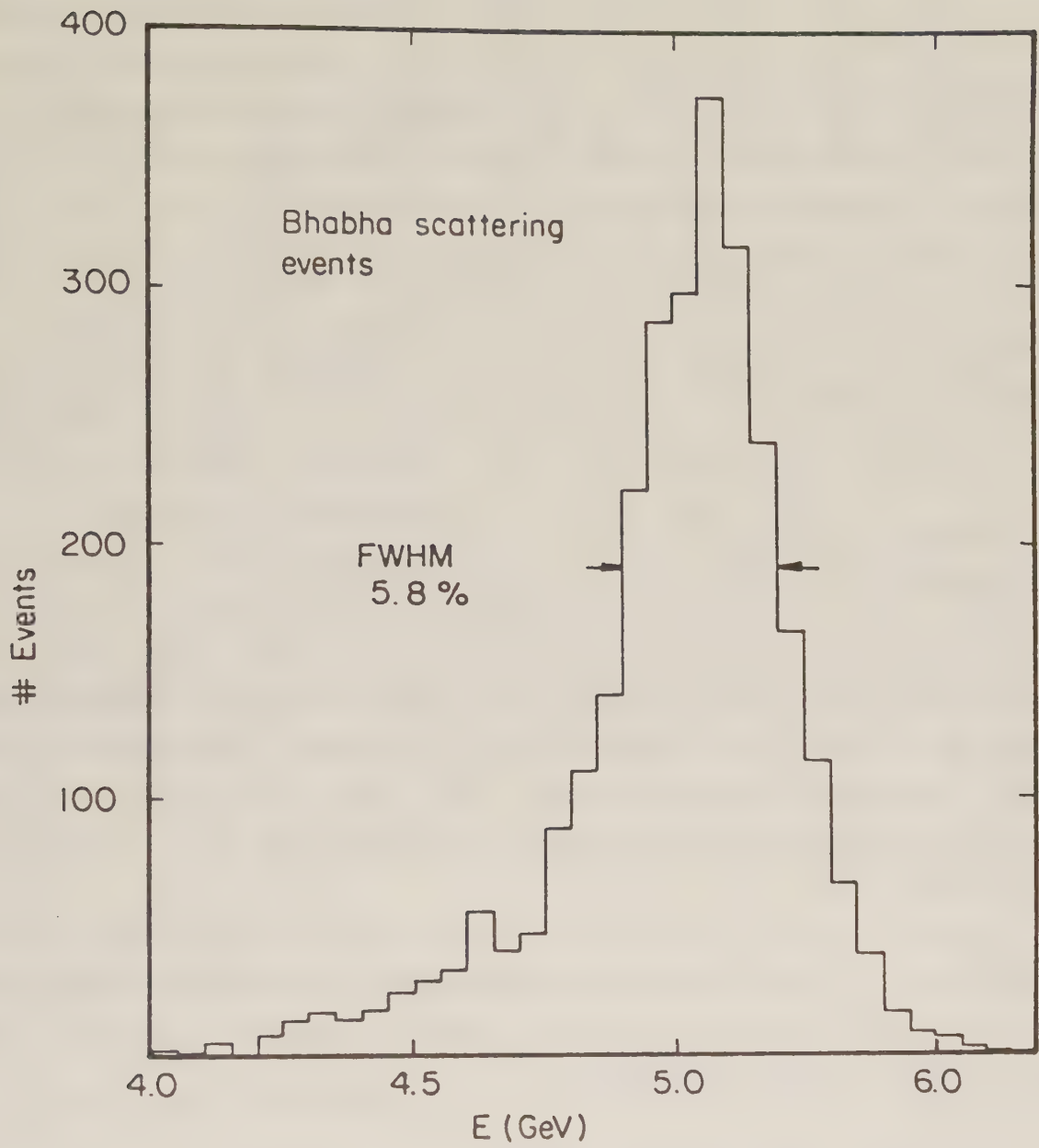


Fig. 3.22 Energy distribution in the central detector of 5 GeV electrons from Bhabha scatters.

IV DATA ANALYSIS

The data samples used in the present analysis were collected after the mini-beta quadrupole installation. The T'' data sample was recorded between November 1981 and February 1982. The integrated luminosity was 15.6 pb^{-1} on the resonance peak and 4.6 pb^{-1} in the continuum below and above the T'' . A year later, from December 1982 to March 1983 the T' data sample was collected, accumulating 29.7 pb^{-1} on the resonance peak and only 1.9 pb^{-1} below and above the T' . To increase the statistics for background studies we have in addition analyzed data from 10 pb^{-1} in the continuum below the T'' , which were taken in the Fall of 1982. To model the background in the inclusive photon spectrum additional data both on the T resonance peak and in the continuum have been used. Table 4.1 summarizes the relevant parameters for the individual running periods.

The main motivation for running first at the T'' resonance was due to the expectation of larger E1 transition rates for $T'' \rightarrow \gamma 2^3P$ than for $T' \rightarrow \gamma 1^3P$. This conclusion resulted from a comparison of thrust distributions⁺⁾ of hadronic events at the T , T' and T'' (from data taken in 1980/1981). The average thrust values after continuum subtraction are higher for the T' and T'' data than for the T data. The highest thrust, however, was observed in the T'' data. This thrust excess indicated larger two-jet like contributions, originating presumably from two gluon decays of 3P_0 and 3P_2 states.

However, after some general remarks about the principles of the analysis we will start first with the discussion of the T' data sample since the signal there is much bigger due to larger statistics and the individual photon lines are clearly resolved.

IV.1 Principles of the Exclusive Analysis

The data samples to be studied essentially result from the exclusive reactions $T' \rightarrow \gamma \chi_b \rightarrow \gamma \gamma T$ and $T'' \rightarrow \gamma \chi'_b \rightarrow \gamma \gamma T(T')$ with a subsequent decay of the $T(T')$ into a $\mu^+\mu^-$ or e^+e^- pair. The signature for such events is very distinctive, since two nearly collinear leptons and two photons are observed in the final state. But because of the small product branching ratios and a low detection efficiency for observing all four particles in the detector, the amount of data expected is small. However, the non

⁺⁾ For definition and further details see IV.2.6

Table 4.1 Relevant parameters for the Υ , Υ' , Υ'' and continuum data samples.

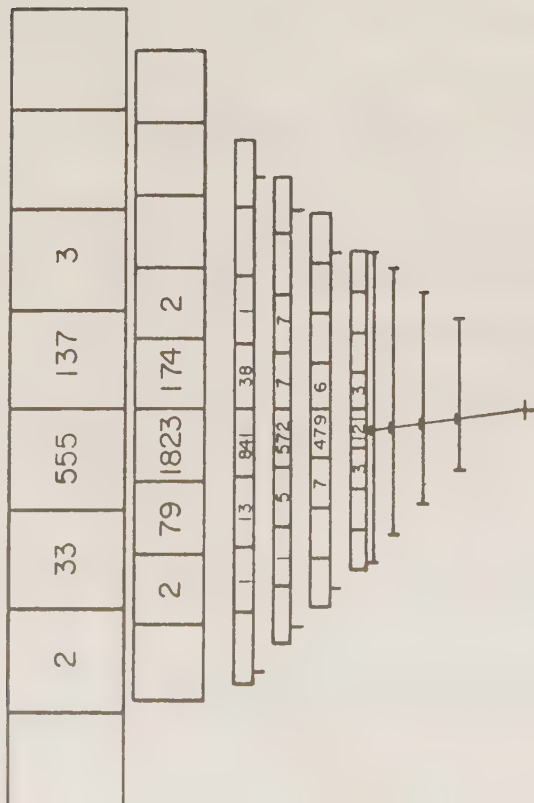
Data Samples	$E_b^{a)}$ [GeV]	$\int L dt$ [pb ⁻¹]	Hadronic events	Hadronic ⁺) eff. [%]	Continuum ⁺) fraction [%]
Υ	$4.713 \leq E_b \leq 4.722$	4.81	72500	82 ± 6	21.2 ± 2.0
Υ'	$4.992 \leq E_b \leq 5.002$	29.71	244700	84 ± 5	$33.3 \pm .8$
Υ''	$5.156 \leq E_b \leq 5.166$	15.54	89800	82 ± 3	$46.2 \pm .5$
continuum below Υ''	$4.999 \leq E_b \leq 5.156$	2.29	5871	61 ± 6	100
above Υ''	$5.166 \leq E_b \leq 5.200$	2.45	6003	"	"
below Υ'	$4.890 \leq E_b \leq 4.992$	1.69	4800	"	"
above Υ'	$4.992 \leq E_b \leq 5.100$	0.18	666	"	"
for exc. below Υ'''	$5.167 \leq E_b \leq 5.250$	11.13	27007	"	"
for inc. below Υ'''	$5.165 \leq E_b \leq 5.260$	18.14	46216	"	"
total cont. (inc.)		24.75	63556	"	"
total cont. (exc.)		17.74	44374	"	"

a) E_b is the beam energy in the CESR energy scale.

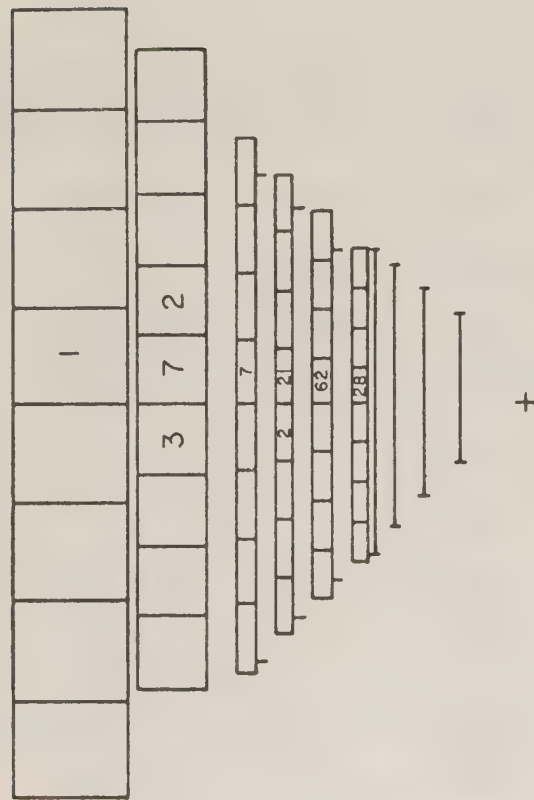
b) The efficiency for hadronic events refers to resonance events only.

c) The continuum fraction is calculated from the measured continuum cross-sections $\sigma_{\text{cont}}(\Upsilon) = (3.20 \pm .30)$ nb, $\sigma_{\text{cont}}(\Upsilon') = (2.74 \pm .07)$ nb, $\sigma_{\text{cont}}(\Upsilon'') = (2.67 \pm .03)$ nb and the corresponding luminosity.

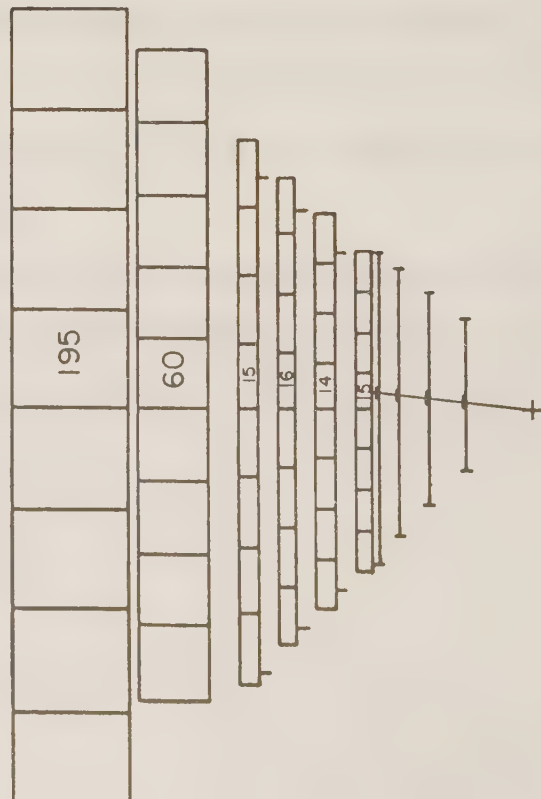
(a) ELECTRON SHOWER (5GeV)



(b) PHOTON SHOWER (125MeV)



(c) MUON TRACK (5GeV)



(d) PIONS

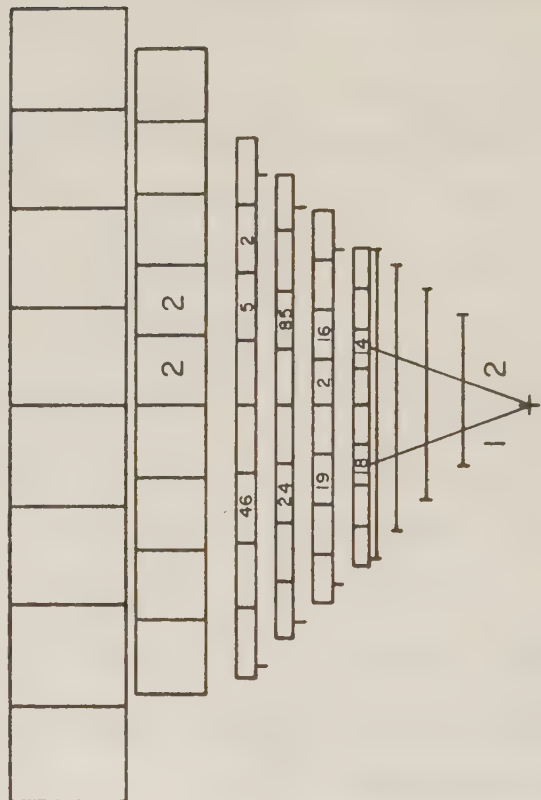


Fig. 4.1 Typical patterns of energy deposition in the central detector for different particles: a) a 5 GeV electron shower, b) a 125 MeV photon, c) a 5 GeV muon, d) a stopping pion (1) and a pion undergoing a nuclear interaction. The numbers shown give the energy in MeV

- magnetic CUSB detector is well suited for measuring exclusive decay modes:
- Due to their characteristic pattern electrons, photons, muons and hadrons are unambiguously identified.
 - Energies of electromagnetic showers in the CD are measured with good resolution.
 - Particle directions are well determined, except for the polar angles of photons in the T' data sample because the OSC's were removed.

IV.1.1 Particle Signature in the CUSB detector

Figure 4.1 displays typical examples for the characteristic energy deposition patterns of electrons, photons, muons and charged hadrons in the detector.

A 5 GeV electron shower in the CD is usually spread out over 3-5 sectors with a large energy penetration into the lead glass (fig. 4.1a). The reconstructed energy is >4.5 GeV except for showers near quadrant boundaries or the CD-EC junctions. More than 90% of the observed shower energy is contained in 2 sectors. From the reconstructed ISC track which points to the shower, electron directions are measured to an accuracy of $\sim 1^\circ$. Due to the fewer available radiation lengths a 5 GeV electron shower in the EC's typically deposits only 2-3 GeV distributed among ~ 9 crystals, and causes a high ionization in both the θ - and ϕ -hodoscopes. Due to the segmentation of the θ -hodoscopes the resolution in θ is $\sigma_\theta \simeq 4.5^\circ$. The resolution in ϕ obtained from the shower cog is $\sigma_\phi = 4^\circ$.

A photon shower in the CD (with $k_\gamma > 50$ MeV) is usually spread out over several adjacent crystals in different planes and sectors (fig. 4.1b). The probability of energy deposition in the Pbc is $< 50\%$ for photons in the 100 MeV range. Because of the removal of the outer strip chambers for the running period at the T' , a moderate position measurement for photons in the T' data sample is only available in the transverse view from the shower cog. This gives an angular resolution for ϕ of $\sigma_\phi \simeq 3^\circ$. The resolution for the polar angle is poor ($\sigma_\theta \simeq 20^\circ$), unless the shower is located near the boundary of the east-west polar halves or the CD-EC boundaries or deposits some energy in the lead glass, in which case we determine $\sigma_\theta = 5^\circ$. However, for photons in the T'' data sample the angles can be determined with a much better accuracy of $\sigma_\theta \simeq 1^\circ$ and $\sigma_\phi \simeq 2^\circ$ by using the OSC's. Usually no ISC track is associated with a photon shower, since the conversion probability is only between 2.7% and 4.7%, depending on the polar angle. However, converted photons show a high ionization in the ISC's of typically ~ 1100 ADC

counts per chamber plane. A photon shower in the EC's also involves several adjacent crystals distributed at least among the inner two rings. For 100 MeV to 800 MeV photons in the region of $\theta=30^\circ-42^\circ$ and $138^\circ-150^\circ$ the shower is entirely contained in the EC's. Hits in the ϕ -hodoscopes are expected at the 6% level due to photons converting in the beam pipe.

A muon shows the typical minimum ionization dE/dx pattern in the CD (fig. 4.1c), i.e. at normal incidence 15 MeV in each of the first four planes, 60 MeV in the fifth plane and 200 MeV in the Pbc. Fluctuations of typically 15% are expected due to the Landau distribution. However, as a function of the track angle the ionization increases up to 65%. Usually the energy is contained in one sector, which lines up with an ISC track from the vertex. Muons that pass the north or south quadrant penetrate the muon filters leaving hits in the muon drift chambers.

A charged pion in the CD usually looks very similar to a muon. However, the track pattern sometimes deviates from a minimum ionizing pattern, because the probability for a nuclear interaction is $\sim 7\%$ (22%) for thin (thick) NaI crystals resulting in higher energy depositions. Slow pions on the other hand are usually stopped in the NaI radial layers. Examples for a slow pion and a pion undergoing a nuclear interaction are shown in fig. 4.1d. In the north and south quadrants pions are absorbed by the iron of the muon filters. A charged pion in the EC's deposits between 15 MeV and 40 MeV in each ring depending on the angle. Usually the energy in each ring is contained in a single crystal. In addition a hit in the ϕ -hodoscopes is observed (95% efficiency).

IV.1.2 The Offline Analysis

The offline analysis of the exclusive cascade decays proceeds in 4 steps:

- i) preselection and classification of raw data
- ii) selection of cascade decay candidates
- iii) final scan by physicists of all selected $\gamma\gamma e e$ and $\gamma\gamma\mu\mu$ candidates.
- iv) complete kinematic reconstruction.

The offline analysis is essentially identical for both the T' and T'' data sets. However, the individual selection criteria, especially those used in the second and third step, differ slightly because of different experimental conditions and different kinematic properties of the individual

transitions. Therefore we list the specific criteria separately in sections IV.2.1 and IV.3.1 and discuss here only the principles of the analysis which hold true for both data sets.

In the first step the raw data tapes have been processed using a program with loose selection criteria. Essentially we have selected all events that have either two back-to-back high energy electromagnetic (em) showers in the CD or EC's together with some additional energy deposited somewhere in the detector, or two back-to-back muons in the CD plus some additional energy. These events classes are labelled as CD-eeX, EC-eeX, and $\mu\mu$ X events, respectively.

More specifically we require:

a) CD-eeX:

- 2 back-to-back em showers with a minimum energy of $E_{\text{NaI}} \geq 1$ GeV for each shower and a maximum acollinearity of ± 2 sectors for the highest energy sector of both showers.
- Additional energy of ≥ 130 MeV in the entire detector excluding 5 sectors for each em shower or, in order to be sensitive to additional minimum ionizing particles, at least 1 NaI crystal in plane 1 with $E \geq 6$ MeV separated by $\geq \pm 3$ sectors from the highest energy sector in each em shower.

b) EC-eeX:

- An EC trigger
- Additional energy ≥ 140 MeV in the CD excluding the 4 CD sectors adjacent to each EC shower, or at least one NaI crystal in plane 1 with energy ≥ 6 MeV separated by $\geq \pm 2$ sectors adjacent to each em shower.

c) $\mu\mu$ X:

- A μ -pair trigger with a total energy $E_{\text{NaI}} \leq 1.5$ GeV in the CD for each event -- in order to reject hadronic events -- and a maximum acollinearity between the 2 minimum ionizing tracks of ± 2 sectors.
- Additional energy ≥ 150 MeV in the entire detector excluding one sector for each muon or at least one crystal in plane 1 with $E \geq 6$ MeV.

These criteria lead to an effective preselection. The primary data amount is reduced down by approximately a factor of 5 eliminating most of the hadronic events, pure Bhabhas, and pure $\mu^+\mu^-$ pairs as well as beam-gas and beam-wall background without losing events of interest. Table 4.2 shows the reduction for a typical raw data tape recorded at the T'. The selected events for each class are written on separate tapes.

In the second step the selection criteria are further tightened to eliminate most of the radiative Bhabhas, radiative $\mu^+\mu^-$ pairs, $\tau^+\tau^-$ pairs and hadronic events that passed the preselection. The remaining events are then processed according to the following scheme:

- 1) Cluster finding in the CD and EC's is performed. First all NaI and Pbc energies within a sector are summed up separately for the 32 sectors in each polar half of the CD. Next one searches for peaks in the resulting sum energy distribution where all sectors with maximum energies are labelled as 'core' sectors. Starting with a core sector all adjacent sectors or adjacent individual crystals with decreasing energy above a threshold of 5 MeV per sector or 2.5 MeV per individual crystal are taken into account for the cluster definition. Isolated crystals with energies greater than 6 MeV are defined as separate clusters. In addition energy profiles across the sectors are checked to separate two adjacent clusters or to identify minimum ionizing tracks. The cluster finding in the EC's is done in a similar way. Next clusters in the east west polar halves and at the CD-EC junctions are matched if the separation between particles is $\Delta\delta \leq 15^\circ$ and $\Delta\phi \leq 20^\circ$. Finally, for each cluster a position vector and the deposited energy is defined. The cluster finding algorithm is $\sim 100\%$ efficient for minimum ionizing particles and for separated em showers with energies > 50 MeV.
- 2) Tracking in the ISC's is performed by the procedure described in III.2.1.
- 3) The lepton pair is identified. For events from the CD-eeX and $\mu\mu$ X samples we require 2 nearly collinear ISC tracks originating at the vertex and pointing to the lepton clusters. For events in the EC-eeX sample we require that the shower centroids in the EC's be nearly collinear. For each electron shower⁺⁾ the energy has to be ≥ 1 GeV in the EC's and ≥ 3.5 GeV in the CD if the shower is well-contained, i.e. 10° away from both the ϕ -gaps at quadrant boundaries and the CD-EC junctions. In the remaining CD region we require ≥ 1 GeV for each electron shower and a sum for both of ≥ 4.0 GeV. For CD-eeX events $\geq 80\%$ of the total CD energy is required to be deposited in the e^+e^- pair.
- 4) The remaining clusters in the CD are examined and classified as 'tracks' or 'photons': A cluster with an ISC track from the vertex pointing to it within 1 sector is called a 'track', otherwise it is called a 'photon'.

⁺⁾ Hereafter the term electron is used to refer to both e^+e^- , as the charge is not determined.

An additional requirement for tracks is that the energy deposition in plane 1 must exceed 6 MeV, while for a photon the total energy must exceed 50 MeV. In addition, for CD-eeX and EC-eeX events a track or photon has to be separated in ϕ by more than 25° from the electron in the same polar half.

- 5) Additional clusters in the EC's are examined. Radial energy deposition requirements are imposed on the clusters in order to reduce background and occasional noisy electronics channels. We require that the cluster energy is distributed among 2 or more crystals and deposits less than 85% of its energy in the inner ring, or less than 90% in one of the outer rings. For EC-eeX events the cluster has to be separated from the electron by more than 27° in ϕ .
- 6) Event selection is performed. Excluding the lepton pair we require 2 to 5 additional particles in the event including at most 2 EC clusters. In addition the energy for each of these particles has to be ≤ 1000 MeV (800 MeV) in the CD (EC) and the energy sum for all additional particles ≤ 1300 MeV.

This procedure provides a rather effective event selection, accepting only $\sim 1.3\%$ of all preselected events. The reduction for the individual classes is shown in table 4.3 using the same representative data set as in the previous table. Besides all $\gamma\gamma\mu\mu$ and $\gamma\gamma ee$ candidates the selected data samples also contain the hadronic cascades $\pi^+\pi^-ee$, $\pi^+\pi^-\mu\mu$, $\pi^0\pi^0ee$, $\pi^0\pi^0\mu\mu$.

In the third step all accepted events are scanned by physicists to search for $\gamma\gamma ee$ or $\gamma\gamma\mu\mu$ events. Only events with two well-separated photons in addition to the lepton pair are selected, where at most one photon is allowed to convert in the beam pipe. In the CD-eeX and EC-eeX event samples the main background results from the QED process $e^+e^- \rightarrow e^+e^-\gamma\gamma$ (double Bremsstrahlung of Bhabha scatters). These gammas are preferentially emitted at small angles with respect to the electron or positron. By requiring both photons to be in the CD, we can reduce that background where one or both photons are emitted by the initial e^+e^- pair. In addition the good energy resolution is maintained for both photons. Due to the smaller background in the $\mu\mu X$ data sample we also accept events with the higher energy photon in the EC's. To eliminate $e^+e^- \rightarrow \tau^+\tau^-$ we require that the muons deposit energy consistent with that for a minimum ionizing particle in the NaI. If the muons are in the south-north quadrant we additionally require that they penetrate the iron toroids and deposit hits in the drift chambers. In order to maintain the good energy resolution, tight fiducial

Table 4.2 Reduction of raw data in the preselection phase.
A typical raw data tape from the T' running period
is shown representing ~2% of all data.

	events processed	events accepted	ratio [%]
μ -pairs	1436	779	54
CD-Bhabhas	6694	1892	28
EC-Bhabhas	3469	1819	52
other	12795	709	6
total	24394	5199	21

Table 4.3 Data reduction in the second analysis phase.
The numbers refer to the same raw data tape
as used in table 4.2.

	events processed	events accepted	ratio [%]
CD-eeX	2601	27	1.0
EC-eeX	1819	15	0.8
$\mu\mu$ X	779	15	1.9
total	5199	57	1.1

Table 4.4 Entire event samples after the handscan.

data sample	L [nb ⁻¹]	$\gamma\gamma ee$ ee in CD	$\gamma\gamma ee$ ee in EC	$\gamma\gamma\mu\mu$	$\pi^0\pi^0 ee$ ee in CD	$\pi^0\pi^0 ee$ ee in EC	$\pi^0\pi^0\mu\mu$
T'	29.7	68	34	34	19	11	15
T''	15.6	49	18	18	10	7	4
cont.	17.7	25	13	1	--	--	--

In addition two events from the multiple cascade transition $T'' \rightarrow \gamma\lambda_b' \rightarrow \gamma\gamma T' \rightarrow \gamma\gamma\gamma\lambda_b \rightarrow \gamma\gamma\gamma\gamma T' \rightarrow \gamma\gamma\gamma\gamma e^+e^-$ and four events from $T'' \rightarrow \gamma\lambda_b' \rightarrow \gamma\gamma\pi^+\pi^- T' \rightarrow \gamma\gamma\pi^+\pi^- e^+e^-$ have been found (see IV.3.9).

cuts and tight overlap cuts are applied to the photon showers.

For calibration purposes we have selected, in addition to $\gamma\gamma ee$ and $\gamma\gamma\mu\mu$ events, $\pi^0\pi^0 ee$ or $\pi^0\pi^0\mu\mu$ cascades. All four photons are required to be in the CD. The number of photon and hadronic cascade events selected in the handscan for the different data samples is shown in table 4.4.

Finally a complete kinematic reconstruction is carried out for the individual events using the measured energies for em showers and the observed directions for all four particles. The measured energies of electrons in the EC's or near quadrant boundaries are adjusted for leakage with a large error assigned to them. The energies of muons, which cannot be measured with the CUSB detector, are kept as free parameters. All measured quantities are inserted into the kinematic fit, which subjects the event to energy and momentum conservation, i.e. $\sum_{i=1}^4 E_i = (M_{T'}, \text{ or } M_{T'',})$ and $\sum_{i=1}^4 \vec{p}_i = 0$. This results in 4 independent constraints (4C fit) for $\gamma\gamma ee$ events, and 2 independent constraints (2C fit) for $\gamma\gamma\mu\mu$ events. To accept the event in the final sample we require for $\gamma\gamma ee$ ($\gamma\gamma\mu\mu$) events a $\chi^2 < 13.3$ (9.2) for 4 (2) dof corresponding to 1% CL.

All selected $\gamma\gamma ee$ and $\gamma\gamma\mu\mu$ events accumulated at the T' have been fitted. Only one $\gamma\gamma ee$ candidate failed the kinematic reconstruction. For the T' data samples the kinematic fit was only applied to $\gamma\gamma ee$ events with e^+e^- in the CD, since for the other samples, due to the removal of the OSC's, only muon directions and photon energies could be measured accurately. Two $\gamma\gamma ee$ events failed the kinematic fits.

IV.2 Photon Cascades from the Transition $T' \rightarrow \gamma\gamma T$

The cascade transition $T' \rightarrow \gamma\lambda_b \rightarrow \gamma\gamma T \rightarrow \gamma\gamma(ee \text{ or } \mu\mu)$ is indicated in a level diagram in fig. 4.2. The photon energies are expected at ~ 125 MeV and ~ 425 MeV, respectively. The product branching ratio for the entire reaction summing over all intermediate λ_b states is $\sim .1\%$.

IV.2.1 Selection Criteria for $T' \rightarrow \gamma\gamma(ee \text{ or } \mu\mu)$

For the $\gamma\gamma\mu\mu$ sample we require the following conditions:

- i) 2 back-to-back ISC tracks, each pointing to a minimum ionizing pattern in the CD, accepted acollinearity $\delta_a := \text{acos}(\vec{\mu}_1 \cdot \vec{\mu}_2) \leq 12^\circ$.⁺
- ii) Vertex cut for ISC tracks: $|x| \leq 2.5\text{cm}$, $|y| \leq 2.5\text{cm}$, $|z| \leq 5\text{cm}$.

⁺) For $T' \rightarrow \gamma\gamma T \rightarrow \gamma\gamma(\begin{smallmatrix} ee \\ \mu\mu \end{smallmatrix})$ the maximum kinematically allowed acollinearity is 7° (both γ 's parallel).

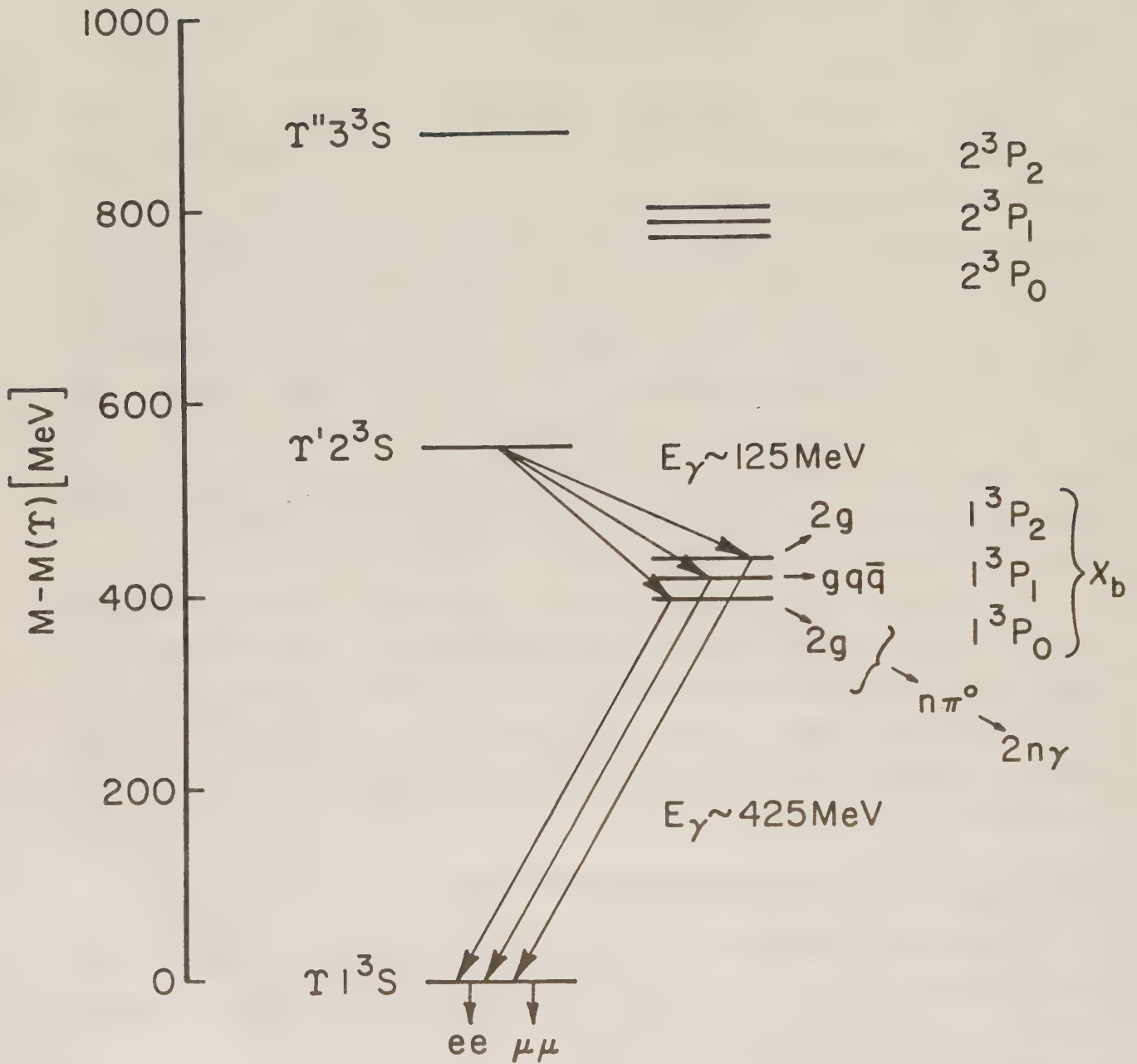


Fig. 4.2 Level diagram showing the exclusive cascade decays $\tau' \rightarrow \gamma 1^3P_J \rightarrow \gamma\gamma \tau \rightarrow \gamma\gamma(e^+e^- \text{ or } \mu^+\mu^-)$. In addition the hadronic decay modes of the 1^3P_J states are indicated.

- iii) Muons in the north-south quadrants must penetrate the muon filter.
- iv) Single photon energies: $50 \leq E_\gamma \leq 900$ MeV
and an energy sum: $150 \leq E_\gamma^{\text{low}} + E_\gamma^{\text{high}} \leq 1000$ MeV
- v) Fiducial volume for photons and muons: (ϕ_L is the local azimuth measured in each quadrant, i.e. $\phi_L \leq 45^\circ$, δ the projected dip angle).
 - for γ_{low} in CD: $|\delta| \leq 40^\circ$ and $\phi_L \leq 39^\circ$
 - for γ_{high} in CD: $|\delta| \leq 42^\circ$ and $\phi_L \leq 41.5^\circ$
 - for γ_{high} in EC: $45^\circ \leq |\delta| \leq 59^\circ$ and $\phi_L \leq 45^\circ$
 - for $\mu\mu$: $|\delta| \leq 27.5^\circ$ and $\phi_L \leq 35^\circ$ for top-bottom
 $|\delta| \leq 30^\circ$ and $\phi_L \leq 43^\circ$ for north-south
- vi) The lower energy photon must always be in the CD, where a photon in the CD is only accepted if it converts in plane 1 to 4 in the NaI.
- vii) The cog of the two photon showers must be separated by ≥ 2 sectors.
- viii) A maximum of one γ -conversion in the beam pipe is allowed. In addition the ionization must be ≥ 7200 ADC counts per track summed over 8 cathode planes.
- ix) Besides the two photons no additional shower or track in the CD or EC's is allowed.

fig. 4.3a shows a typical $\gamma\gamma\mu\mu$ cascade event. Both muons have an ISC track pointing to a minimum ionizing pattern in the CD and penetrate through the iron of the muon filters, as shown in fig. 4.3b. In addition two photon showers with energies of $E_\gamma^{\text{low}}=125$ MeV and $E_\gamma^{\text{high}}=423$ MeV are visible, showing no tracks in the ISC's.

For the $\gamma\gamma ee$ sample we require similar conditions:

- i) 2 back-to-back ISC tracks in the CD from the interaction region or 2 back-to-back clusters in the EC, with an acollinearity of $\delta_a \leq 12^\circ$ in CD and $\delta_a \leq 20^\circ$ in EC. Each ISC track must point to the shower cog to within $\pm 10^\circ$.
- ii) Vertex cut as for $\gamma\gamma\mu\mu$.
- iii) Energy sum of the e^+e^- system: $E_{ee} := E(e^+) + E(e^-) \geq 8$ GeV for well-contained showers in the CD, $E_{ee} \geq 4$ GeV outside the good energy region, and $E_{ee} \geq 2$ GeV in the EC's.
- iv) Both photons in CD requiring a conversion in planes 1 to 4 in the NaI.
- v) Single photon energies: $50 \leq E_\gamma \leq 900$ MeV
and an energy sum: $150 \leq E_\gamma^{\text{low}} + E_\gamma^{\text{high}} \leq 1000$ MeV.
- vi) Fiducial volume for photons and electrons:
 - for γ_{low} in CD: $|\delta| \leq 40^\circ$ and $\phi_L \leq 39^\circ$
 - for γ_{high} in CD: $|\delta| \leq 42^\circ$ and $\phi_L \leq 41.5^\circ$
 - for ee in CD: $|\delta| \leq 42^\circ$ and $\phi_L \leq 42.5^\circ$
 - for ee in EC: $45^\circ \leq |\delta| \leq 68^\circ$ and $\phi_L \leq 45^\circ$

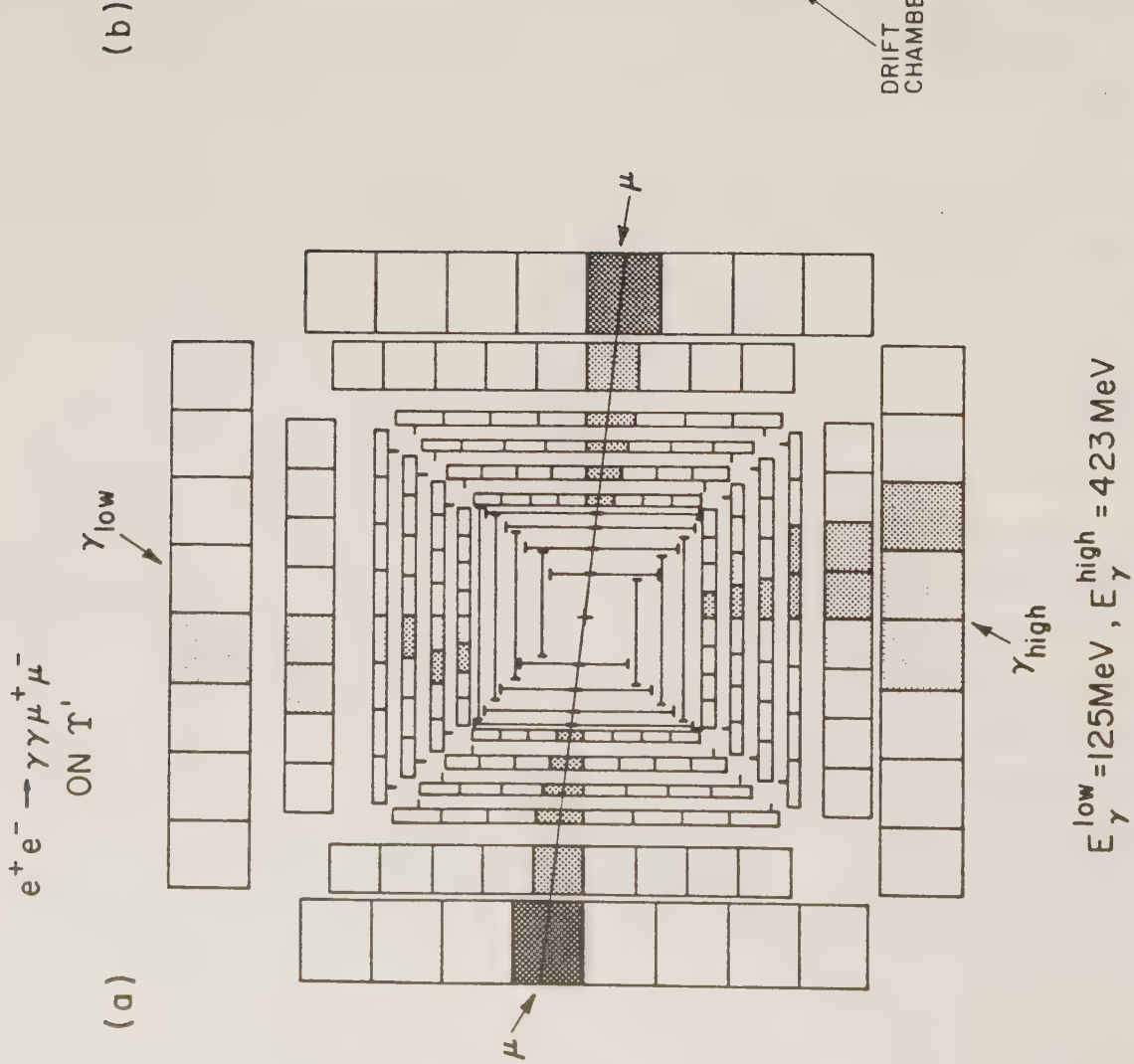


Fig. 4.3 Event display of an $T' \rightarrow \gamma 1^3P_1 \rightarrow \gamma\gamma T' \rightarrow \gamma\gamma\mu^+\mu^-$ decay,
a) showing the 4 particles in the central detector
b) showing that both muons penetrate the iron of the muon filters

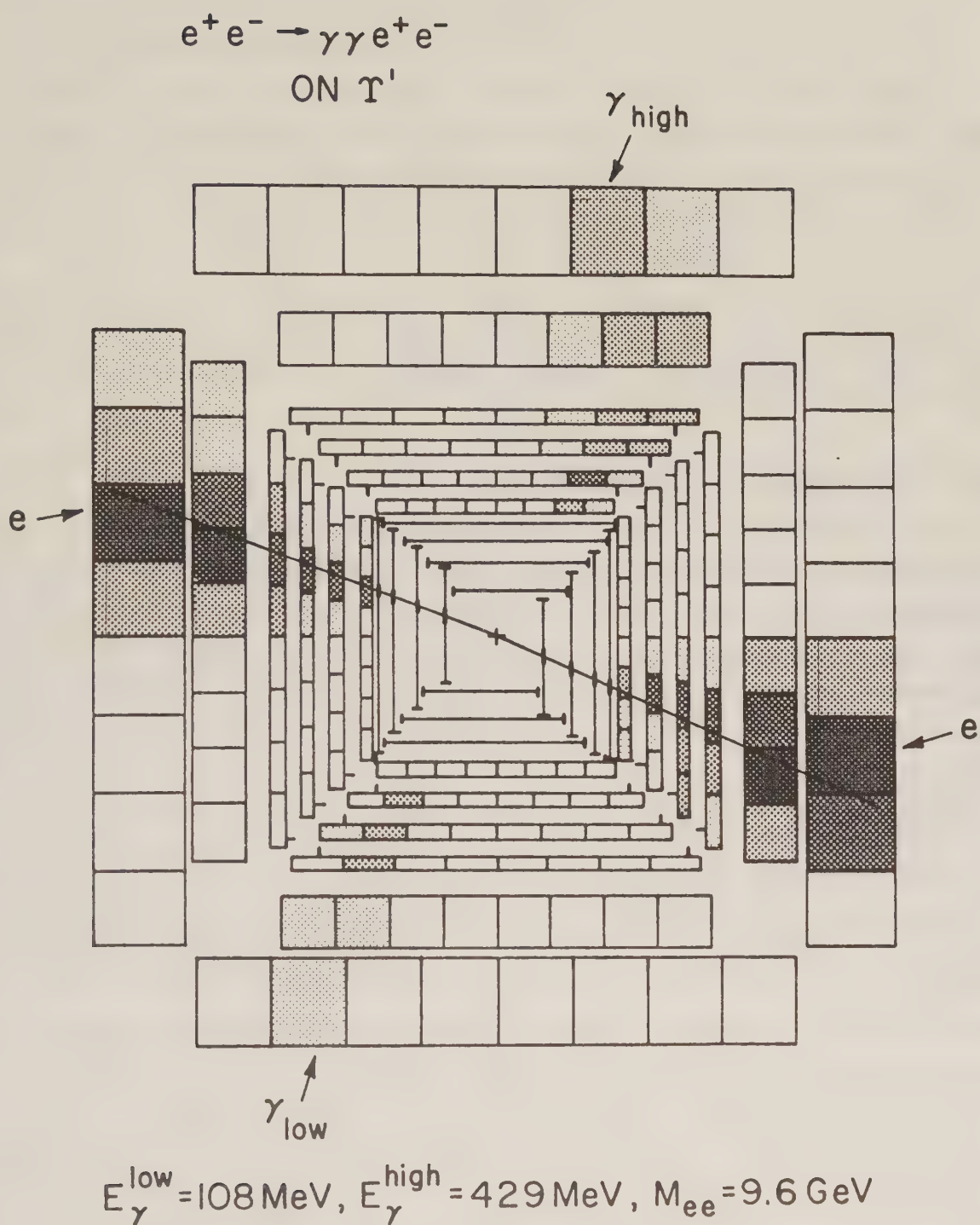


Fig. 4.4 Event display of an $\Upsilon' \rightarrow \gamma 1^3P_2 \rightarrow \gamma\gamma \Upsilon \rightarrow \gamma\gamma e^+e^-$ decay.

- vii) The photon shower cog must be separated by ≥ 3 sectors ($\geq 25^\circ$) from the electron shower cog if both particles are in the same (opposite) polar half. The cog of the two photon showers must be separated by ≥ 2 sectors. To reduce background from $e^+e^- \rightarrow e^+e^-\gamma\gamma$, at least one photon must be separated from the closest electron shower by $\geq 45^\circ$.
- viii) A maximum of one γ -conversion in the beam pipe is allowed.
- ix) No additional showers or tracks are allowed in the CD or EC's.
- x) The unconstrained kinematic fit (4C fit) is required to give a $\chi^2 < 13$ for 4 dof, corresponding to 1% CL.

In fig. 4.4 an example for a typical $\gamma\gamma ee$ cascade event is shown. The two large em showers have an invariant mass of $M_{ee} = 9.6$ GeV and the photon shower energies of $E_\gamma^{\text{low}} = 108$ MeV and $E_\gamma^{\text{high}} = 429$ MeV.

IV.2.2 Determination of Photon Energies

To determine the correct energies of photon showers, we first sum up the energies of all individual NaI crystals and Pbc blocks contributing to the shower. For simplicity all six planes in a sector are added. This is justified as fluctuations due to electronics noise are small as indicated by the narrow pedestal distributions. Requiring at least 2 MeV per sector, usually 2-3 sectors contribute to a shower. For this purpose we use the NaI energies determined from the source calibration constants⁺) whereas Pbc energies are obtained from the calibration technique discussed in III.3.4.

To compensate for energy losses in the inactive material and energy leakage at quadrant boundaries or the CD-EC junctions we adjust all shower energies by angle dependent correction factors, which are determined with an EGS Monte Carlo (MC) program [FN 78]. The MC program simulates the shower development of photons and electrons in the CUSB detector. The configuration of the detector is taken into account including the correct size of the individual calorimeter elements, and the amount of inactive material both within a sector and between adjacent sectors. The intrinsic resolution of the calorimeter material is also included, using $\sigma_i = 2\%/\sqrt[4]{E}$ (E in GeV). For a fixed initial energy E_i distributions of the observed energy are generated as a function of the projected dip angle δ and the local azimuth angle ϕ_L . For angles $|\delta| \leq 35^\circ$ and $\phi_L \leq 35^\circ$ the generated distributions have a gaussian shape. Due to energy leakage at the quadrant

⁺) The source calibration constants are obtained directly from the ^{60}Co and ^{137}Cs sources as described in III.3.3.

boundaries of the CD-EC junctions they become asymmetric with a low energy tail at larger angles. For each δ and ϕ_L a correction factor is determined by:

$$f(\delta, \phi_L) = E_i/E_{obs} \quad (4.1)$$

where E_{obs} is the average of the corresponding distribution. Using a fine grid for both angles we can perform a mapping of the entire detector by interpolating smoothly between the generated data. fig. 4.5 shows $f(\delta, \phi)$ for 125 MeV photon showers in the CD vs ϕ_L for different δ . For $\delta \leq 25^\circ$ and $\phi_L \leq 25^\circ$ the correction for inactive material is 8%, independent of angles. The distributions have an rms resolution of 5.3%. At large angles $f(\delta, \phi_L)$ increases very rapidly due to leakage effects. For example at $\delta=40^\circ$ and $\phi_L=40^\circ$ we obtain a correction of 32% with a rms spread of 15%. The correction factors $f(\delta, \phi)$ are nearly independent of the initial energy in the range of 80 to 800 MeV. For photons in the EC's the correction is 20% on the average, since due to fewer radiation lengths leakage effects already dominate the energy losses in the inactive material. To perform the energy correction for photons in the CD normally an average projected dip angle of $\delta \approx 30^\circ$ is used, unless δ can be determined more accurately from the cog of the energy distribution in the lead glass or from showers that are located near the boundary of the east-west polar halves or the CD-EC junctions.

The energy resolution of the photon showers is essentially determined by the losses in the inactive material and the energy leakage. Including both effects, we therefore obtain for 125 MeV photons an average resolution of $\sigma_E/E=5.8\%$. The energy dependence of the resolution can be approximated by $\sigma_E/E=3.5\%/\sqrt[4]{E_i}(\text{GeV})$ if leakage effects at large angles are neglected.

IV.2.3 Absolute Calibration and Energy Resolution

In order to cross-check both the absolute energy scale and the resolution of photons in the 130 MeV energy range, we have analyzed the photons from the exclusive transition $\Upsilon' \rightarrow \pi^0 \pi^0 \Upsilon \rightarrow \gamma \gamma \gamma \gamma (e^+ e^- \text{ or } \mu^+ \mu^-)$ with the same method discussed above. Though the individual photon energies are not monochromatic, ranging from 20 to 400 MeV, these photons are well suited for this purpose because:

- i) The energy sum of all four photons is fixed by the $\Upsilon' - \Upsilon$ mass difference. In the lab system there is a small correction for the Υ recoil.
- ii) For ~60% of the photons the energies range from 100 to 200 MeV.

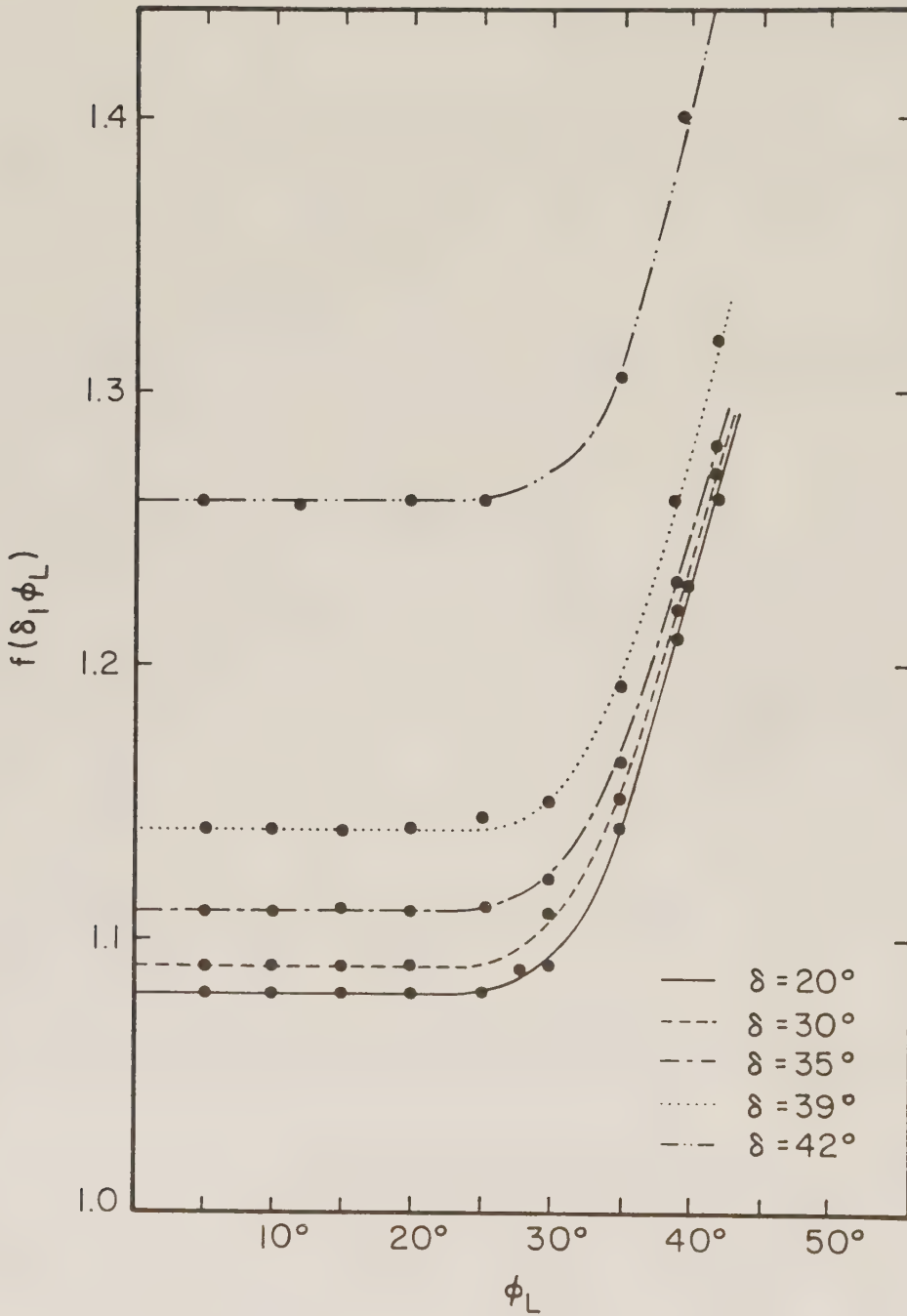


Fig. 4.5 Energy correction factors for photon showers in the central detector without outer strip chambers versus the local azimuth angle ϕ_L for different projected dip angles. The data shown are obtained from a Monte Carlo simulation of the shower development in the central detector. The curves are an interpolation between the generated data.

- iii) They are from the same data sample as the photon cascades.
- iv) The number of $ee\gamma\gamma\gamma$ and $\mu\mu\gamma\gamma\gamma$ events expected in our data sample is quite large because of the high luminosity of 29.7 pb^{-1} , and the relatively large branching ratio of $\text{BR}(\tau' \rightarrow \pi^0 \pi^0 \tau) \simeq 10\%$.

To retain the good energy resolution we require that all four photons are well separated and in the CD. At least three photons have to be inside the fiducial volumes defined in IV.2.1. However, to maintain good statistics at most one photon is allowed to be outside these fiducial regions. This gives a total of $45 \pi^0 \pi^0 ee$ and $\pi^0 \pi^0 \mu\mu$ events.

Figure 4.6 shows for these events the spectrum of the energy sum. The spectrum peaks $(8 \pm 3) \text{ MeV}$ below the expected position of 556 MeV as predicted by MC studies for a $\tau' - \tau$ mass difference of 560.6 MeV (CESR energy scale)⁺ and recoil effects [Fo 84].

The agreement between observation and prediction is excellent if one considers the following effects, each causing systematic uncertainties at the 1% level:

- i) For $\delta \geq 35^\circ$ or $\phi_L \geq 35^\circ$ the correction factors are on the average a bit too small due to the asymmetric MC distributions.
- ii) For showers near the quadrant boundaries the shower cog provides too small a value for ϕ_L due to the energy leakage, resulting also in slightly too small correction factors. Similar effects occur for δ at the CD-EC junction.
- iii) For most of the lower energy em showers an average projected dip angle has to be used because δ cannot be determined from the lead glass or the shower topology, which also gives a smaller correction factor $f(\delta, \phi_L)$ on the average.
- iv) As MC studies of shower developments show a few MeV of energy are sometimes deposited at large transverse distances from the shower, and so are not included in the shower energy summation.

We therefore correct the energy of each photon shower upward by 2%. The observed spectrum has an rms spread, $\sigma_E = 20.4 \text{ MeV}$, while MC calculations predict $\sigma_E = 19.5 \text{ MeV}$. This result is in agreement with a single photon resolution of 5.8% at $E_i = 125 \text{ MeV}$, especially if we take into account that

⁺) Since the Cornell conference on photons and leptons the $\tau' - \tau$ mass difference is measured from high precision g-2 experiments to $M_{\tau'} - M_\tau = 563.5 \text{ MeV}$. Therefore the expected peak position has to be corrected by 2.9 MeV to $\sim 558.9 \text{ MeV}$.

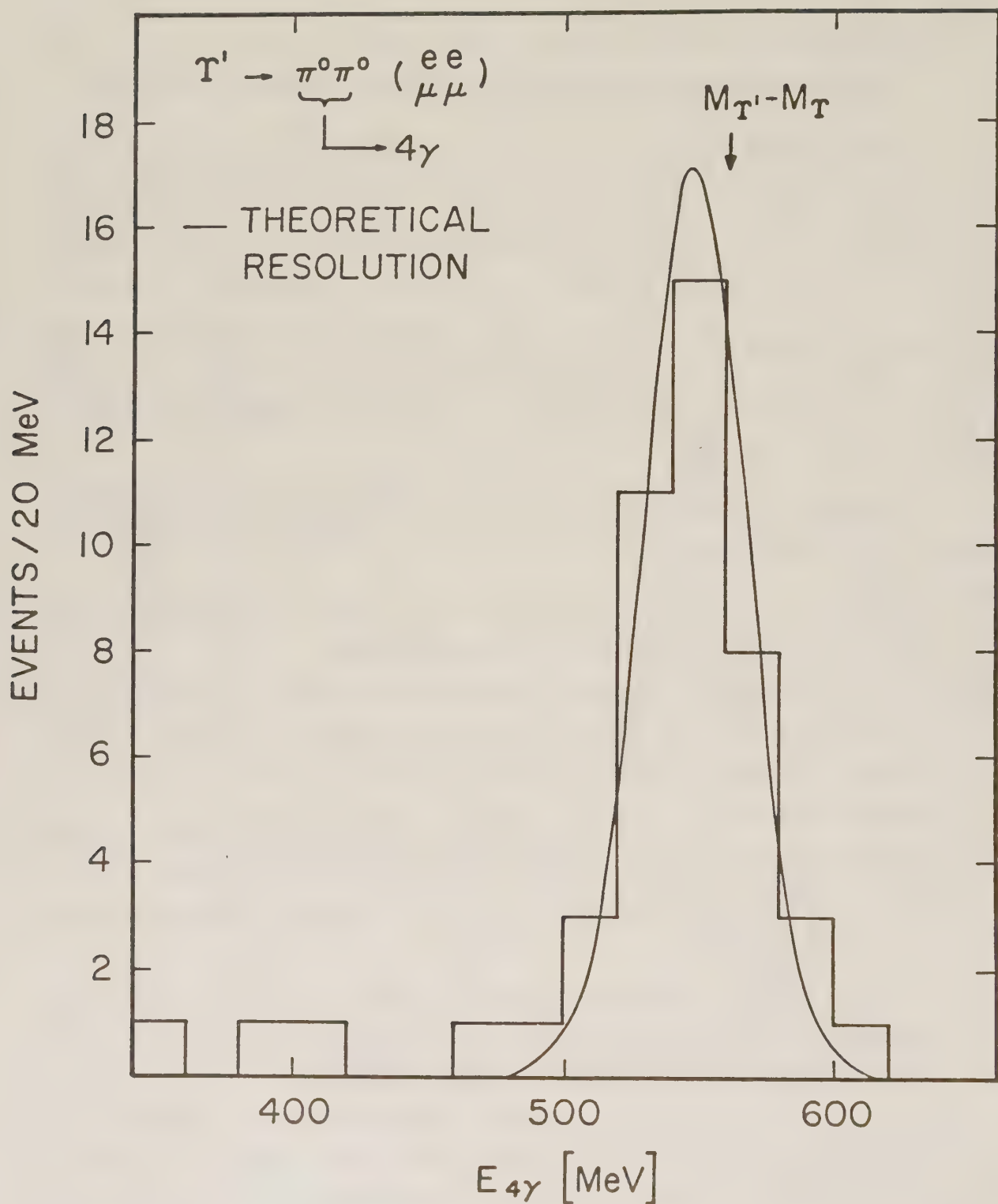


Fig. 4.6 Spectrum of the energy sum of the four photons for the transition $T' \rightarrow \pi^0 \pi^0 T \rightarrow \gamma \gamma \gamma \gamma (e^+e^- \text{ or } \mu^+\mu^-)$. The arrow indicates the energy difference for the transition between the T' and T . The solid line represents a gaussian with the predicted rms error from Monte Carlo calculations.

this method gives a slightly pessimistic value for σ_E , since $\sim 2/3$ of the events have one photon located at a quadrant boundary or near the CD-EC junction with a resultant poorly measured energy. For example if we only select events where all four photons are perfectly measured (i.e. 13 events) we obtain an rms resolution of 12 MeV for the energy sum.

IV.2.4 Acceptance and Detection Efficiency

The acceptance for events from the cascade transitions $T' \rightarrow \gamma 1^3P_J \rightarrow \gamma \gamma T \rightarrow \gamma \gamma (\mu\mu \text{ or } ee)$ is given by the six-dimensional integral:

$$a_J = \frac{\int_{(4\pi)^3} d\Omega A(\Omega) \cdot W_J(\Omega) \cdot f(\Omega)}{(4\pi)^3} \quad (4.2)$$

with

$A(\Omega)$: geometric acceptance determined by the geometric arrangement of the detector

$W_J(\Omega)$: angular distributions of cascade transitions via $J=0, 1$, or 2^3P_J states

$f(\Omega)$: a function that accounts for losses due to the overlap of two particles

$$d\Omega = d(\cos\theta_1) d\phi_1 \cdot d(\cos\theta_2) d\phi_2 \cdot d(\cos\theta_3) d\phi_3$$

For convenience we choose the lab frame $^+$) as coordinate system. Hence (θ_1, ϕ_1) , (θ_2, ϕ_2) and (θ_3, ϕ_3) define polar and azimuth angles of the lower energy photon γ_1 , the higher energy photon γ_2 and the final $e^-(\mu^-)$ pair in the lab frame, respectively. $^{++}$)

The normalization of eq.(4.2) is guaranteed by the normalization of the angular distribution:

$$\int_{(4\pi)^3} d\Omega W_J(\Omega) = 1 \quad (4.3)$$

The angular distributions used are those derived by Brown and Cahn for E1 transitions under the assumption that the initial e^+e^- beams are unpolarized and that the polarizations of photons and leptons in the final state remain unobserved [BC 75]. Since the expressions for the $W_J(\Omega)$ are rather lengthy, we have listed the explicit formulas in Appendix B. In this section we only

$^+)$ In the lab frame the z-axis is defined by the initial electron direction and the x(y)-axis by the normal to the south (top) quadrant.

$^{++})$ The acollinearity between the lepton pair is neglected.

give a few examples to demonstrate that the individual angular dependence is generally weak. After averaging over all azimuth angles and all polar angles except one particular θ_i one obtains the smoothly varying functions:

$$\bar{W}_0(\theta_1) = 3/4(1 + \cos^2\theta_1) \quad (4.4a)$$

$$\bar{W}_0(\theta_2) = 1 \quad (4.4b)$$

$$\bar{W}_1(\theta_1) = 9/8(1 - (1/3) \cdot \cos^2\theta_1) \quad (4.5a)$$

$$\bar{W}_1(\theta_2) = 15/16(1 + (1/5) \cdot \cos^2\theta_2) \quad (4.5b)$$

$$\bar{W}_2(\theta_1) = 39/40(1 + (1/13) \cdot \cos^2\theta_1) \quad (4.6a)$$

$$\bar{W}_2(\theta_2) = 73/80(1 + (21/73) \cdot \cos^2\theta_2) \quad (4.6b)$$

For all three angular distributions the dependence θ_3 is identical to $\bar{W}_J(\theta_2)$. Note that except for $\bar{W}_0(\theta_1)$ all other functions show a rather weak angular dependence.

The geometric acceptance for cascade events in an ideal detector which records every particle inside its active volume is simply given by the two-valued function:

$$A(\Omega) := \begin{cases} 1 & \text{for all four particles inside the active detector volume} \\ 0 & \text{otherwise} \end{cases} \quad (4.7)$$

We can factorize $A(\Omega)$ into 3 square distributions $A_i(\theta_i, \phi_i)$ characterizing the individual acceptance of γ_{low} , γ_{high} and the final leptons, respectively:

$$A(\Omega) = A_1(\theta_1, \phi_1) \cdot A_2(\theta_2, \phi_2) \cdot A_3(\theta_3, \phi_3) \quad (4.8)$$

In a realistic detector arrangement the functions $A_i(\theta_i, \phi_i)$ deviate slightly from a square distribution because of particle losses near the detector edges. However, if we restrict $A(\Omega)$ to the fiducial volumes defined in IV.2.1 these effects become small. They will be taken into account in the detection efficiency.

The function accounting for losses due to particle overlaps is defined by:

$$f(\Omega) := \begin{cases} 0 & \text{if two particles overlap within a volume element } \Delta\Omega_{ij} \\ 1 & \text{otherwise} \end{cases} \quad (4.9)$$

In general we have to account for the 5 overlap regions of γ_{low} with γ_{high} and each photon with each lepton⁺), where the individual regions are defined by:

$$|\phi_1 - \phi_2| \leq \Delta\phi_{12} \text{ and } \cos\theta_1 \cdot \cos\theta_2 > 0 \quad \text{for } \gamma_{low} - \gamma_{high} \quad (4.10a)$$

$$|\phi_i - \phi_3| \leq \Delta\phi_{i3} \text{ and } \cos\theta_i \cdot \cos\theta_3 > 0 \quad \text{for } \gamma_i - e^-(\mu^-) \quad (4.10b)$$

$$|\phi_i - \phi_3 - \pi| \leq \Delta\phi_{i3} \text{ and } \cos\theta_i \cdot \cos(\pi - \theta_3) > 0 \quad \text{for } \gamma_i - e^+(\mu^+) \quad (4.10c)$$

According to the selection criteria the values for the azimuthal overlap cuts are $\Delta\phi_{12} = 19^\circ$ for the $\gamma - \gamma$ separation, $\Delta\phi_{i3} = 29^\circ$ (27°) for the $e - \gamma$ separation in the sample with ee in the CD(EC's) and $\Delta\phi_{i3} = 11^\circ$ for $\mu - \gamma$ separations. The polar overlap region consists of the entire polar half since due to the detector configuration two particles inside one polar half are not separable if they overlap in ϕ .

To evaluate the integral in eq.(4.2) for each event class and each angular distribution we have used a simplified MC simulation. First, for each event a set of 3 angle pairs ($\cos\theta_i, \phi_i$) was generated for one particular transition using the correct angular distribution $W_J(\Omega)$. Next unit vectors for the directions of γ_{low} , γ_{high} , and the final $e^-(\mu^-)$ were constructed, assuming that the interaction vertex was located at the origin. The direction of the $e^+(\mu^+)$ was set opposite to that of the $e^-(\mu^-)$, neglecting the acollinearity between the final leptons. Acollinearity effects were taken into account in the trigger efficiencies. The fiducial volume of the detector was simply approximated by the angular cuts in δ and ϕ_L defined in the selection criteria in IV.2.1. No requirements on particle energies and no cuts on the energy profile of the individual particles were made. Events were only accepted if all four vectors were located inside the fiducial volumes and if all four vectors were separated according to the overlap cuts defined above. The results obtained for a_J with this procedure for each transition and each event class are listed in table 4.5. For all event classes a_0 is slightly smaller than a_2 whereas a_1 is on the average 17% larger than a_2 . For comparison in a detector covering almost the entire solid angle like the Crystal Ball the acceptances a_J are expected to be nearly identical.

⁺) Only the $\gamma\gamma\mu\mu$ sample with one photon in the EC shows 2 overlap regions. For $\gamma\gamma ee$ events with ee in the EC's we have to exclude the sectors in the CD adjacent to the ee showers, due to splashes from the EC into the CD.

Table 4.5 Acceptances and efficiencies for $\tau' \rightarrow \gamma\gamma\tau$

	ee $\gamma\gamma$ ee in CD	ee $\gamma\gamma$ ee in EC	$\mu\mu\gamma\gamma$ $\gamma\gamma$ in CD	$\mu\mu\gamma\gamma$ one γ in EC	sum over all categories
α_0	.098 $\pm$.001	.038 $\pm$.001	.082 $\pm$.001	.018 $\pm$.001	.236 $\pm$.002
ε_0	.088 $\pm$.003	.033 $\pm$.002	.069 $\pm$.003	.013 $\pm$.002	.203 $\pm$.005
α_1	.122 $\pm$.001	.056 $\pm$.001	.096 $\pm$.001	.027 $\pm$.001	.302 $\pm$.002
ε_1	.110 $\pm$.004	.048 $\pm$.003	.081 $\pm$.003	.020 $\pm$.002	.259 $\pm$.006
α_2	.103 $\pm$.001	.047 $\pm$.001	.084 $\pm$.001	.024 $\pm$.001	.258 $\pm$.002
ε_2	.093 $\pm$.003	.040 $\pm$.003	.071 $\pm$.003	.017 $\pm$.002	.221 $\pm$.006
η_{tr}	.97 $\pm$.02	.96 $\pm$.02 ⁺)	.90 $\pm$.02	.87 $\pm$.02 ⁺)	
η_{sc}	.97 $\pm$.02	.92 $\pm$.05	.97 $\pm$.03	.90 $\pm$.10	
$\eta_{\gamma\gamma}$	.96 $\pm$.01	.97 $\pm$.01	.97 $\pm$.01	.94 $\pm$.04	

$\eta_{\gamma\gamma}$ contains the probability that a photon converts in the fifth layer and the probability that both γ 's are separated by $<45^\circ$ from both the e^+ and e^- showers.

⁺) These numbers include a factor of .97 accounting for runs which could not be used in the analysis because of ADC problems in the EC's.

To determine the detection efficiency ε_J for the photon cascades we have to account for the following effects:

- i) Trigger efficiencies η_{tr} : For $\gamma\gamma ee$ events η_{tr} is expected to be uniform in θ and ϕ except near the detector boundaries. Inside the fiducial volumes, losses are expected to be only $\lesssim 3\%$. Acollinearity effects are negligible because of the large electron showers. For $\gamma\gamma\mu\mu$ events η_{tr} shows a slight ϕ dependence which is due to inefficiencies in the μ -pair trigger logic and the narrow gaps between adjacent counters ($< 2\%$). Additionally losses occurring near the edges of the muon counters are enhanced by acollinearity effects. We have estimated $\eta_{tr}(\gamma\gamma\mu\mu)$ with MC studies including all these effects in addition to the probability for recording two hits in opposite muon counters. The results are listed in table 4.5.
- ii) Event recovery efficiency of the analysis program η_{pr} : The analysis program only shows inefficiencies if two particles are close together or if, due to energy leakage, one particle fails the minimum energy requirements defined in the selection criteria. However, both effects are already covered by the large overlap cuts and the individual particle fiducial volumes, respectively.
- iii) Scanning efficiencies η_{sc} : For each event class η_{sc} has been determined by comparing two independently hand-scanned data sets and normalizing the overlapping events to the total number of events accepted in both scans.
- iv) Photon selection efficiency $\eta_{\gamma\gamma}$: Besides the effects covered already by the fiducial volumes, overlap cuts and trigger efficiencies we have to correct for the probabilities that a photon in the CD converts in the 5th layer ($\sim 2\%$ effect), and that the γ -e separation for both photons in the $\gamma\gamma ee$ samples is $< 45^\circ$. In the $\gamma\gamma\mu\mu$ sample with one γ in the EC's we have to account for $\sim 4\%$ losses due to photon shower profile cuts.

Since all these effects are nearly angle independent we can express ε_J to a good approximation by:

$$\varepsilon_J = \eta_{tr} \cdot \eta_{sc} \cdot \eta_{\gamma\gamma} \cdot \alpha_J \quad (4.11)$$

The individual results of the detection efficiency for each transition and event class are also given in table 4.5. For the $\gamma\gamma ee$ sample we obtained detection efficiencies of $\varepsilon_0(\gamma\gamma ee)=12\%$, $\varepsilon_1(\gamma\gamma ee)=16\%$, $\varepsilon_2(\gamma\gamma ee)=13\%$, while for the $\gamma\gamma\mu\mu$ sample we got $\varepsilon_0(\gamma\gamma\mu\mu)=8\%$, $\varepsilon_1(\gamma\gamma\mu\mu)=10\%$, and $\varepsilon_2(\gamma\gamma\mu\mu)=9\%$.

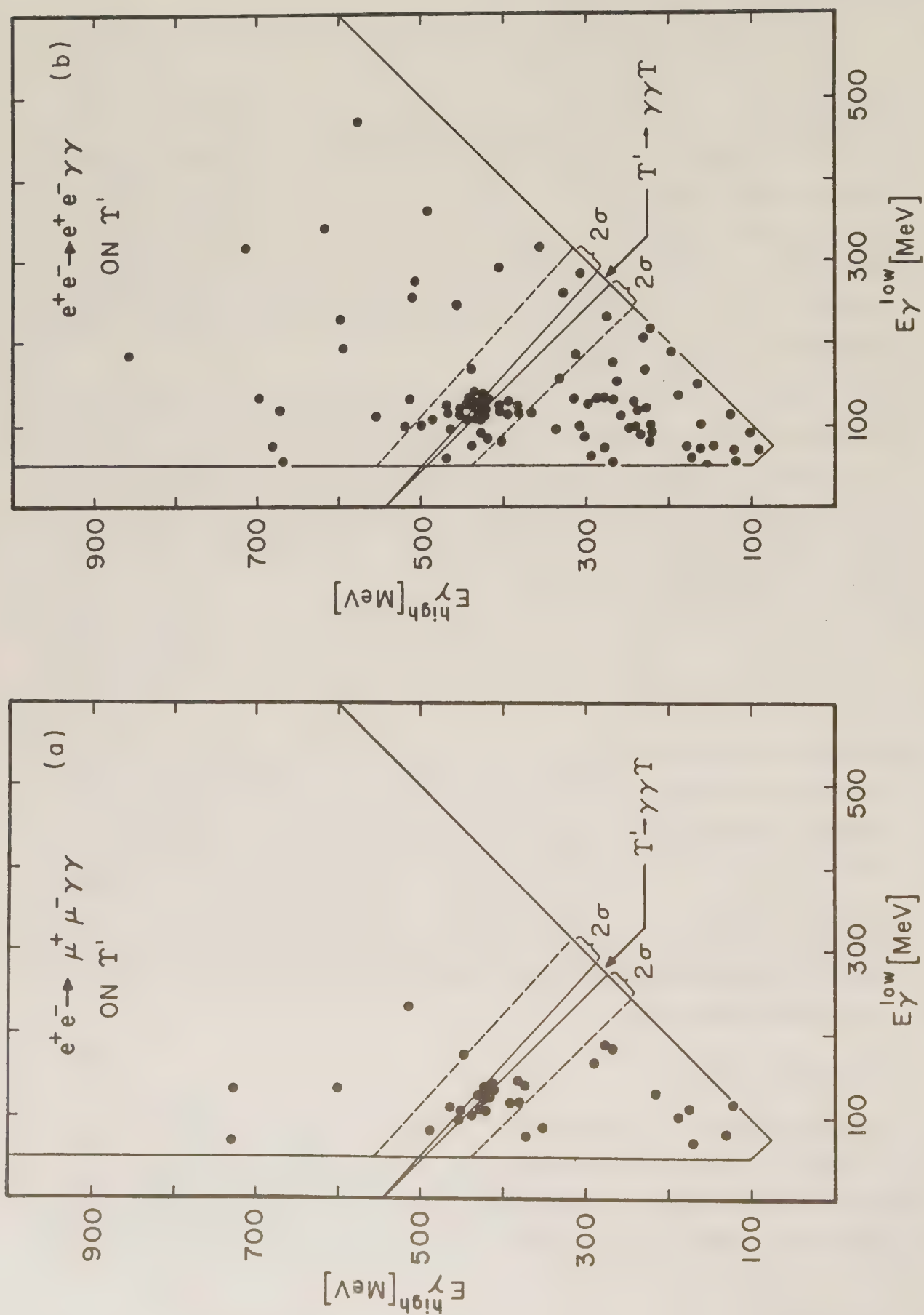


Fig. 4.7 Scatter plot of the higher versus the lower energy photon,

a) from $\tau' \rightarrow \nu\bar{\nu}\mu^+\mu^-$, b) from $\tau' \rightarrow \nu\bar{\nu}e^+e^-$

For example, by using the distribution W_1 one determines the acceptances of the individual lepton pairs in the appropriate fiducial volumes to be 38% for $\mu^+\mu^-$, 58% for e^+e^- in the CD and 25% for e^+e^- in the EC's. The photon acceptances calculated with W_1 are 57% for γ_{low} in the CD and 56% (12%) for γ_{high} in the CD(EC's), respectively.

IV.2.5 Results on the Exclusive Decays $T' \rightarrow \gamma\gamma(ee \text{ or } \mu\mu)$

IV.2.5.1 Signal for χ_b Production in the $\gamma\gamma$ Correlation Plot

Fig. 4.7a shows the scatter plot of the lower energy photon versus the higher energy photon for the $\gamma\gamma\mu\mu$ sample after the handscan. The region for the transition $T' \rightarrow \gamma\gamma T$ corrected for the T recoil and including Doppler broadening⁺) is indicated by the solid lines. The dashed lines show the $\pm 2\sigma$ limits of our energy resolution (i.e. ± 54 MeV). 18 out of 34 events cluster around $(E_{\gamma}^{low}, E_{\gamma}^{high}) \sim (125, 425)$ MeV. We interpret this as evidence for radiative transitions via an intermediate state, presumably the χ_b states. As shown in fig. 4.7b a similar result is found in the $\gamma\gamma ee$ sample, where we have combined all handscan selected events with e^+e^- in the CD or the EC's. 34 out of 100 events cluster around $(E_{\gamma}^{low}, E_{\gamma}^{high}) \sim (125, 425)$ MeV. However, this plot contains a much larger amount of background events, especially at low energies (see next section).

To demonstrate further that we indeed observe photon transitions to the ground state T fig. 4.8 shows the spectrum of the energy sum $E_{\gamma}^{low} + E_{\gamma}^{high}$ for all events of figs. 4.7a and 4.7b. In addition, we have added two events from the multiple photon cascades $T'' \rightarrow \gamma\chi_b' \rightarrow \gamma\gamma T' \rightarrow \gamma\gamma\gamma\chi_b \rightarrow \gamma\gamma\gamma\gamma T$ which we have found in the analysis of the $\pi^0\pi^0$ data sample at the T'' (for details see IV.4). The spectrum has a pronounced peak at (548 ± 4) MeV which agrees with the expected position of 550 MeV when T recoil and Doppler broadening effects are included. The dashed curves indicate the expected $\gamma\gamma$ -background from $\pi^0\pi^0$ decays and the QED process $e^+e^- \rightarrow e^+e^-\gamma\gamma$.

Another cross-check is provided by plotting the invariant e^+e^- pair mass M_{ee} , which is obtained from a kinematic fit of each event. The resulting distribution of M_{ee} for events with electrons in the CD is shown

⁺) For $E_{\gamma}^{low} = 125$ MeV the Doppler broadening is 11 MeV. The maximum recoil (both photons parallel) is 16 MeV.

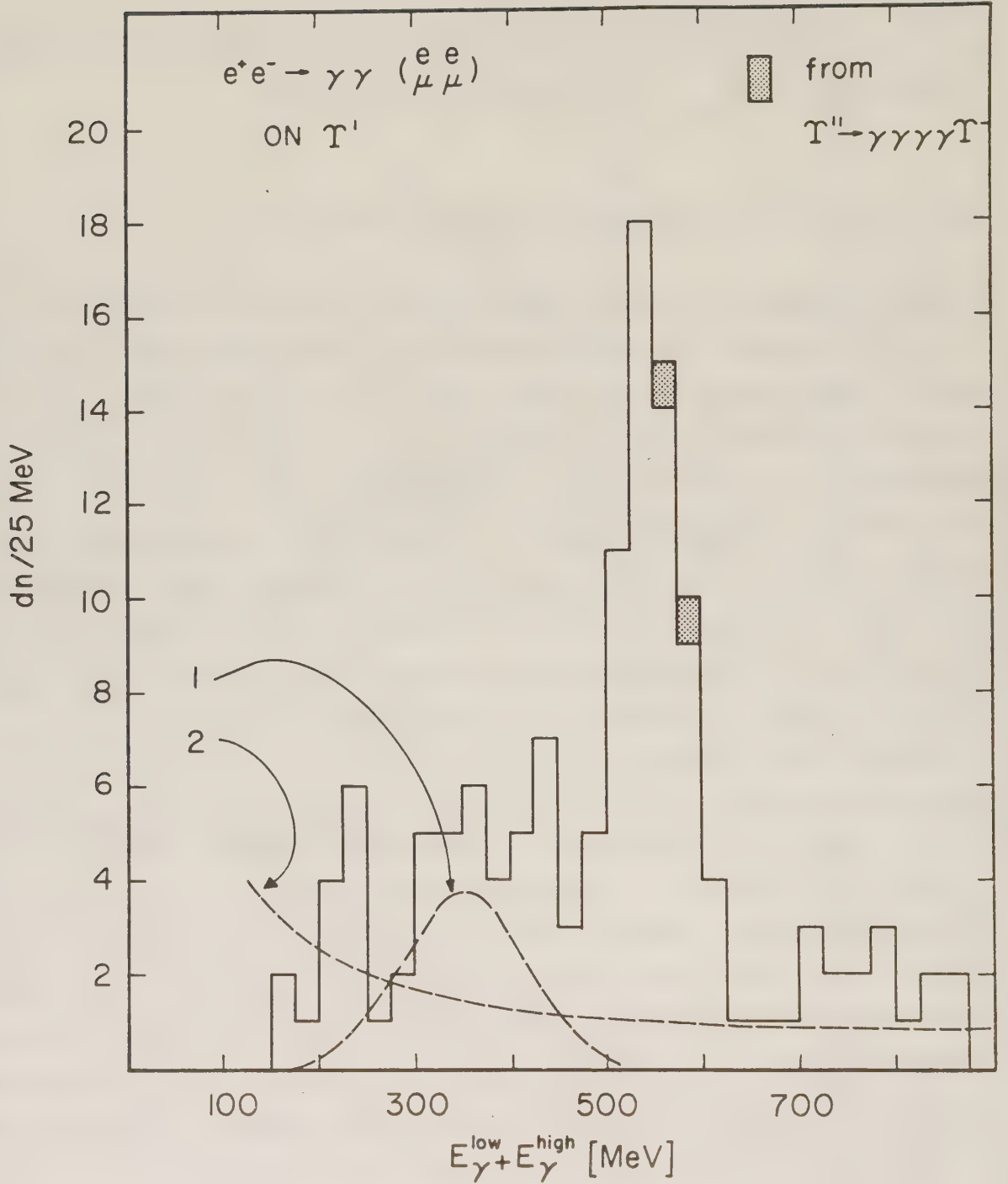


Fig. 4.8 Spectrum of the energy sum of the two photons for all events in figs. 4.7a, 4.7b. In addition two events from the multiple cascades $\tau'' \rightarrow \gamma\lambda_b' \rightarrow \gamma\gamma\tau' \rightarrow \gamma\gamma\gamma\lambda_b \rightarrow \gamma\gamma\gamma\gamma(\tau \rightarrow e^+e^-)$ have been included. The lines indicate estimates for: (1) the background from $\pi^0\pi^0$ decays and (2) the contribution from double Bremsstrahlung of Bhabha scatters.

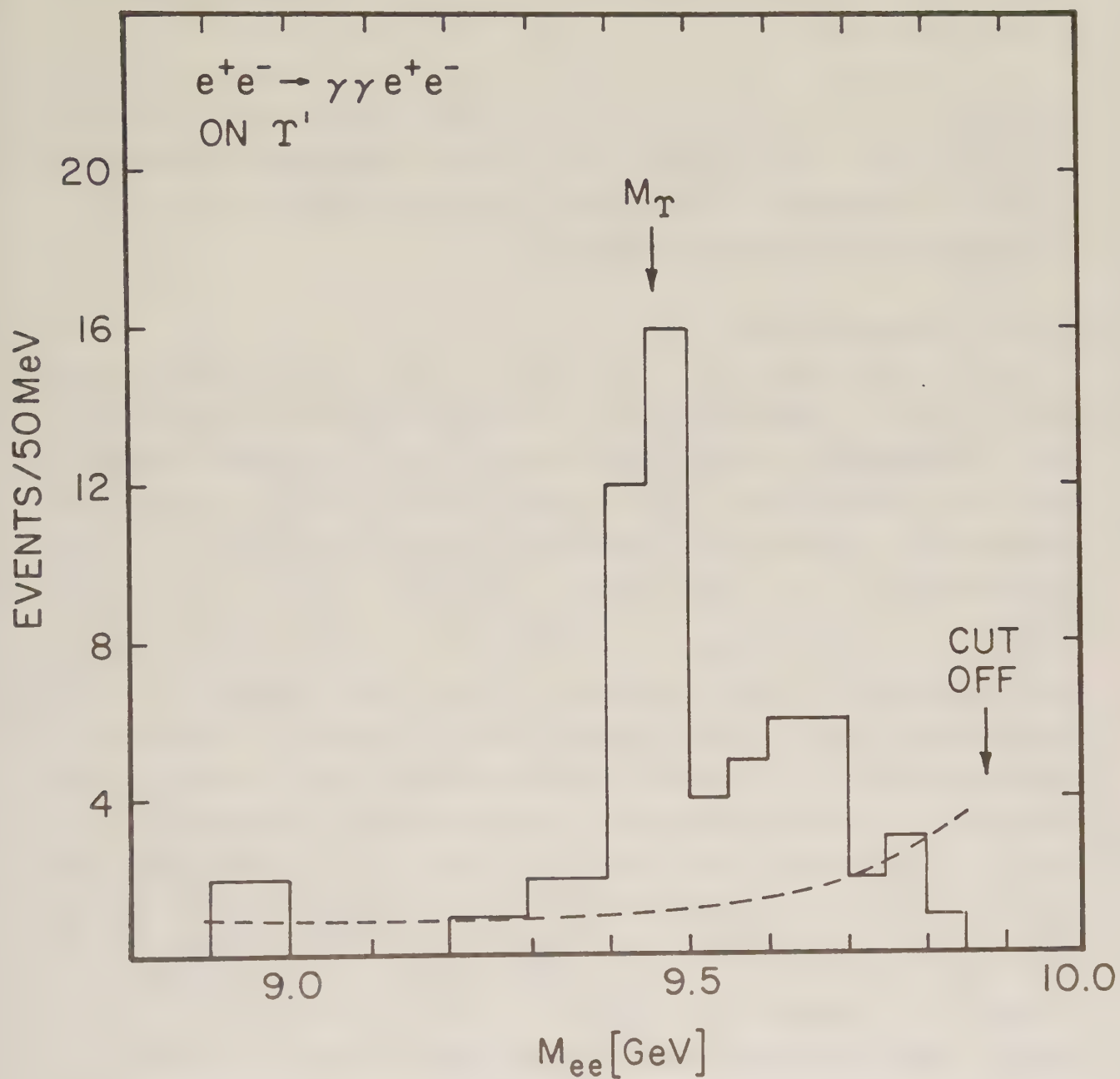


Fig. 4.9 Invariant e^+e^- mass spectrum from $T' \rightarrow \gamma\gamma e^+e^-$ events with both leptons in the central detector. The enhancement around 9.65 GeV is due to background from $\pi^0\pi^0$ decays. The dashed lines indicate estimates for the background from double Bremsstrahlung of Bhabha scatters.

in fig. 4.9. A pronounced peak is observed at (9453 ± 6) MeV in good agreement with the Υ mass. This indicates that for these events the e^+e^- pair results from an Υ decay supporting the hypothesis of radiative cascade decays. The enhancement around 9.65 GeV is due to background from the transition $\Upsilon' \rightarrow \pi^0 \pi^0 \Upsilon$.

The assignment of the χ_b mass is ambiguous. However, from the observation of a strong signal around 125 MeV in the inclusive photon spectrum obtained from hadronic events of the same running period (see IV.2.6) we conclude that the χ_b states are located ~ 125 MeV below the Υ' , in agreement with theoretical predictions.

IV.2.5.2 Background Studies

The data samples in figs. 4.7a and 4.7b contain some background from other reactions. A background source specific to the $\gamma\gamma\mu^+\mu^-$ sample results from the reaction $e^+e^- \rightarrow \tau^+\tau^- \rightarrow (\mu^+\nu_\mu\bar{\nu}_\tau)(\rho^-\nu_\tau)$ or its charge conjugate. Since the ρ decays nearly 100% through $\rho^\pm \rightarrow \pi^\pm \pi^0 \rightarrow \pi^\pm \gamma\gamma$, we observe one genuine muon, a charged minimum ionizing pion being misidentified as a muon and two photons in the final state. The total cross section for this reaction is estimated to .07 nb resulting from a τ pair production cross section of $\sigma(e^+e^- \rightarrow \tau^+\tau^-) = 0.86$ nb at $\sqrt{s} = M_\tau$, and the branching ratios $BR(\tau \rightarrow \mu\nu\bar{\nu}) = 18.5\%$ and $BR(\tau \rightarrow \rho\nu) = 21.6\%$. The entire process has been simulated with the Lund MC program [Sj 80]. Applying in addition an acollinearity cut of 12° between the muon and pion, using the same photon energy cuts as in the data analysis, and requiring all four particles to be located in the corresponding fiducial volume we predict at most four such events in the entire $\gamma\gamma\mu\mu$ sample. If we further require muon identification (i.e. penetration through the muon filter) about half of these events can be removed. As an additional cross check a scan for $\gamma\gamma\mu^+\mu^-$ candidates in continuum data equivalent to 17.5 pb^{-1} has been performed using the same selection criteria as for resonance events. One event was found which agrees perfectly with the MC prediction after scaling it by the ratio of integrated luminosities.

A background source specific to the $\gamma\gamma ee$ sample results from double Bremsstrahlung of Bhabha scatters. Due to the geometry of our fiducial volume mainly final state radiation contributes. Characteristic graphs are shown in fig. 4.10. Due to the $1/E$ dependence of the radiated photon we expect this contribution to peak at the tip of the correlation plot and the 50 MeV boundary. The contribution of double Bremsstrahlung is determined

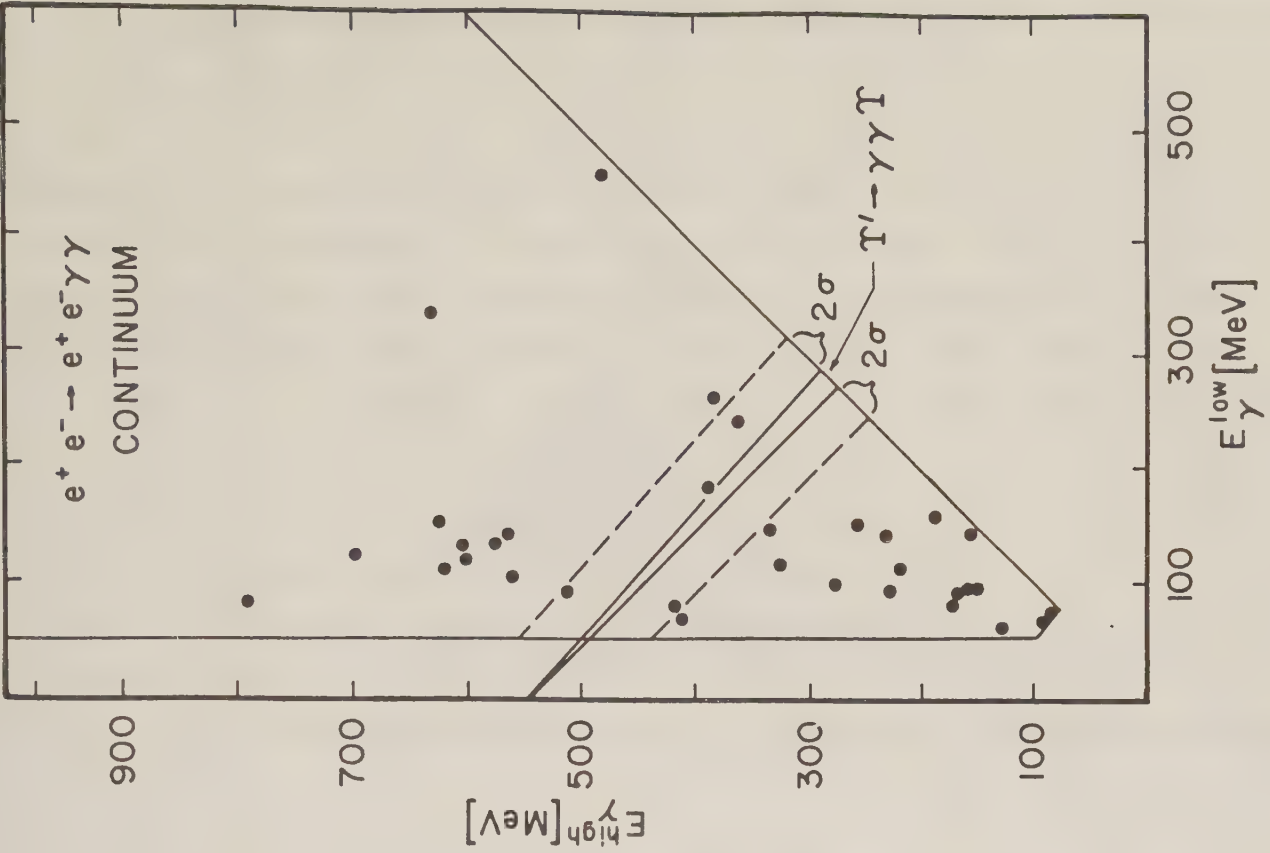


Fig. 4.11 Scatter plot of the higher vs the lower energy photon from $\gamma\gamma \rightarrow e^+e^-$ events in the continuum.

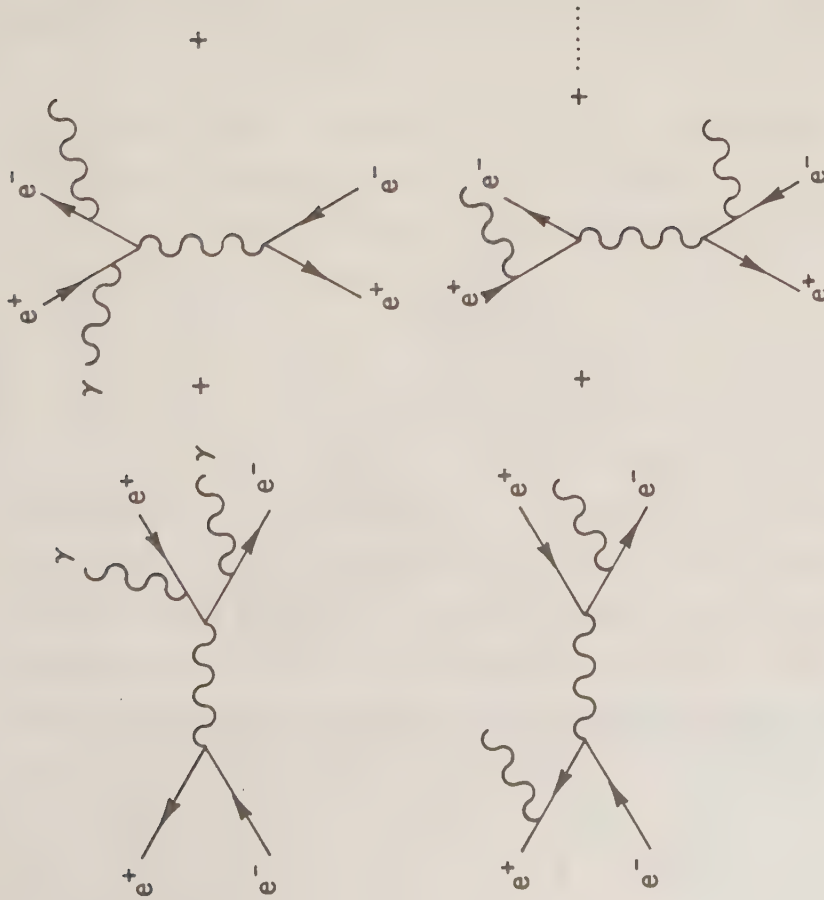


Fig. 4.10 Lowest order Feynman diagrams for double Bremsstrahlung of Bhabha scatters.

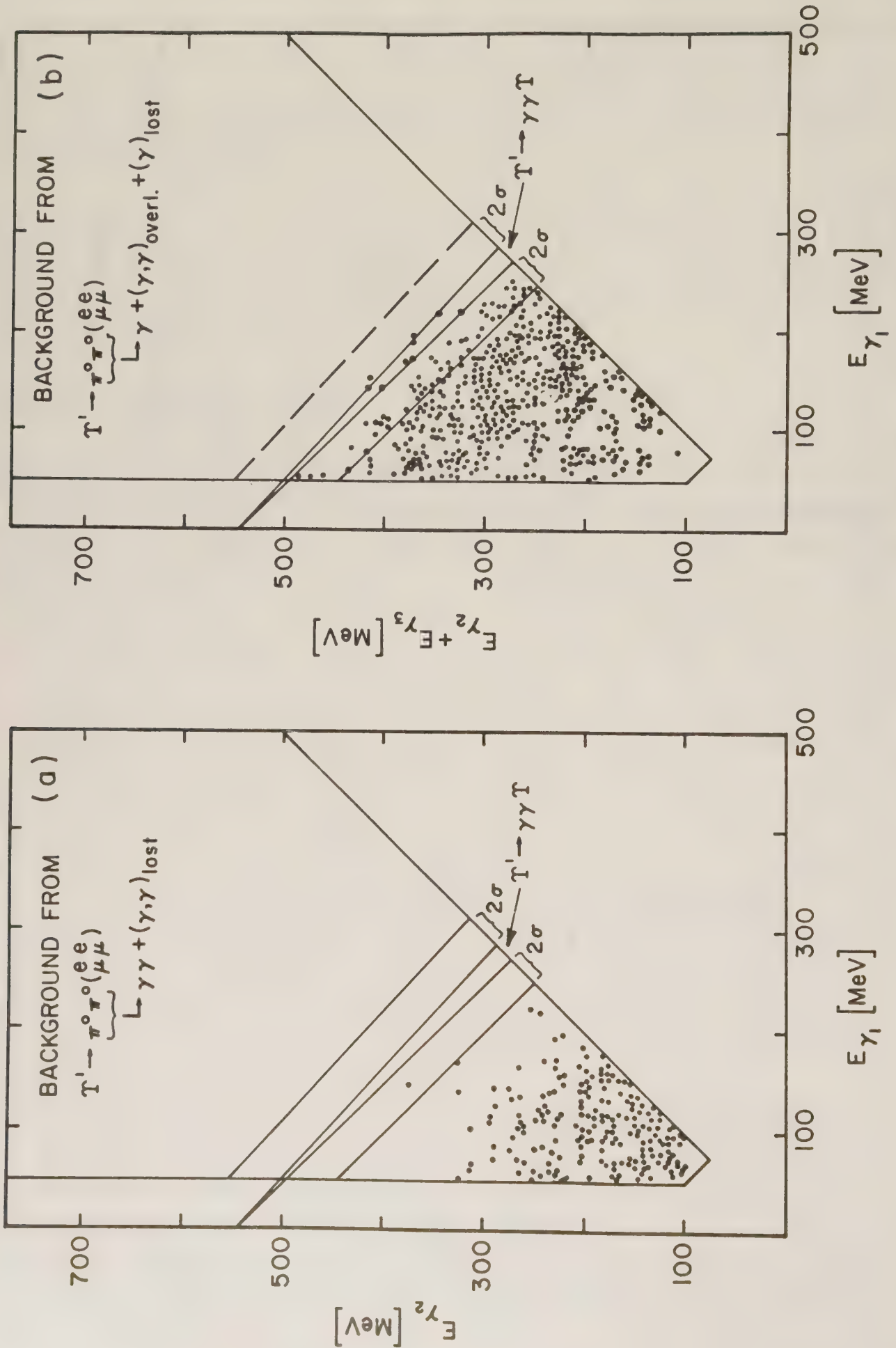


Fig. 4.12 Background simulation from 45 observed $\tau' \rightarrow \pi^0 \pi^0 \tau$ decays with all four photons in the central detector, plotting the lower versus the higher energy photon for:
a) all 6 combinations of 2 out of the 4 photons

from two independent methods, both giving consistent results. First, we have performed a search for $\gamma\gamma e$ candidates in the continuum sample (17.5 pb^{-1}), with the selection criteria of the T' data obtaining the correlation plot shown in fig. 4.11. The photon energies have been adjusted by $M_{T'}/2E_{\text{beam}}$ to simulate the photon spectrum at $\sqrt{s}=M_{T'}$. We observe 4 events in the 2σ bands. However, to increase statistics we have also included data equivalent to 15.6 pb^{-1} from the analysis of the transition $T' \rightarrow \gamma\gamma T(T') \rightarrow \gamma\gamma e$ (see figure 4.27b), finding in addition three events inside the same energy bands. We therefore estimate a total of 6 ± 3 double radiative Bhabha events inside the 2σ bands after scaling by the ratio of integrated luminosities. If we additionally restrict E_{γ}^{low} to energies $90 \leq E_{\gamma}^{\text{low}} \leq 160$ MeV the background contribution reduces to 2 ± 1 events. In the second method we have estimated the background using 5000 observed single radiative Bhabhas. Assuming that the soft photon approximation is valid one can randomly combine two photons according to the energy distribution of photons from single radiative Bhabhas thus generating a sample of double Bremsstrahlung events. Analyzing the resulting two photon sample with our selection criteria we have obtained 6 ± 0.8 events inside the entire 2σ -bands and 2 ± 0.3 events in the restricted region $90 \leq E_{\gamma}^{\text{low}} \leq 160$ MeV.

For the $\gamma\gamma\mu$ sample double Bremsstrahlung (from initial state radiation) is only a minor background source. From a MC generation of muons and photons in the entire solid angle a total cross section of $4.4 \times 10^{-4} \text{ nb}$ was obtained, yielding at most 1 event for our entire data sample [Re 82].

A background source affecting both the $\gamma\gamma e$ and $\gamma\gamma\mu$ sample results from the hadronic cascade decay $T' \rightarrow \pi^0 \pi^0 T \rightarrow \gamma\gamma\gamma\gamma(e^+e^- \text{ or } \mu^+\mu^-)$ in which only two out of the four photons are observed. The remaining photons are undetected because either they escape through regions not covered by the calorimeter (corresponding to approximately 14% of the total solid angle), or overlap with an electron or another photon. We estimate detection efficiencies for such background events of $\epsilon = (1.3 \pm 0.2)\%$ in the muon sample and $\epsilon = (2.7 \pm 0.5)\%$ in the electron sample. Using the branching fractions $\text{BR}(T' \rightarrow \pi^0 \pi^0 T) \simeq 10\%$ and $B_{\mu\mu}(T) = 2.9\%$ we expect 7 ± 2 and 16 ± 3 events in the entire correlation plots of figs. 4.7a and 4.7b, respectively. To study the energy dependence of this background source we have simulated two photon events from our observed $\pi^0 \pi^0$ data sample by either omitting photons or by merging showers. The correlation of the higher energy photon versus the lower energy photon for all combinations of two out of the four gammas is plotted in figure 4.12a. The energy correlation of two overlapping photons

versus one of the remaining photons is shown in figure 4.12b for all combinations of three out of the four gammas. In addition we have simulated this process with the EGS MC program by generating the hadronic cascade decay in our detector and selecting those events with 2 gammas observed. The two background estimates only differ at low values of the energy sum, which we attribute to scanning inefficiencies for detecting low energy photons ($E_\gamma < 40$ MeV). However, the plots indicate that these background events populate the energy region below the 2σ -bands nearly uniformly. Since the background displayed in fig. 4.12b only contributes at the 10% level and the remaining dominant contribution from fig. 4.12a contains only a very small fraction ($< 2\%$) of events in the critical energy range above 440 MeV we estimate at most 1 event inside the 2σ -bands in the $\gamma\gamma ee$ and $\gamma\gamma\mu\mu$ samples, respectively.

Contributions from possible η -transitions with $\eta \rightarrow \gamma\gamma$ are negligible and do not overlap with cascade events [Fo 84]. Since the two photons are slow they are back-to-back thus populating the energy region around (270,270) MeV in the scatter plot. In figure 4.7b 3 events are observed in that region. However the invariant photon mass $M_{\gamma\gamma}$ of these events is inconsistent with η production. To summarize we estimate a total background of 7 ± 3 (2 ± 2) events inside the entire 2σ -bands for the electron (muon) sample which reduces to 2 ± 1 (1 ± 1) events if we further restrict γ_{low} to the energy range $90 < E_\gamma^{low} < 160$ MeV.

IV.2.5.3 χ_b Fine Structure

In order to search for fine splitting of the χ_b states we have combined the data from both the $\gamma\gamma\mu\mu$ and $\gamma\gamma ee$ samples, accepting only events inside the 2σ -bands. In addition, we have included the two events from the multiple photon cascades $T'' \rightarrow \gamma\chi_b' \rightarrow \gamma\gamma T' \rightarrow \gamma\gamma\gamma\chi_b \rightarrow \gamma\gamma\gamma\gamma T$. After correcting E_γ^{high} for the Doppler shift (adjusted according to the γ - γ opening angle) we have constrained the energy sum of both photons to the appropriate $T'-T$ mass difference reduced by the T -recoil (i.e. 550 MeV for CESR energy scale) where the adjustment of each photon energy is proportional to the resolution.⁺) This procedure is very helpful in compensating for small systematic uncertainties in the absolute energy calibration. We estimate the remaining systematic error scale to be < 1

⁺) A kinematic fit of the entire event including the electrons provides no further improvement due to the relatively large uncertainties in the electron energies and photon directions.

MeV. In addition, we also gain a small improvement in the energy resolution of $\sim 16\%$, as MC studies indicate, yielding 5% at 125 MeV. The resulting spectrum for the lower energy photon is plotted in Fig. 4.13. Two clearly separated peaks are visible, showing a 15σ and a 23σ effect above continuum background, respectively. We have fitted the spectrum with the minimization program MINUIT [JR 78] using two gaussian distributions on top of a constant background of $1/4$ events per bin. Position and height of the gaussians were left as free parameters whereas the resolutions have been fixed to the MC derived value of 5.0%. The fit yields line positions at (105.5 ± 2.6) MeV and (127.6 ± 1.5) MeV with a χ^2 of 6.8 for 11 degrees of freedom (dof), corresponding to a confidence level (CL) $> 80\%$. If we allow resolution and background to vary freely the line positions are found to be very stable. However, background and resolution are strongly correlated, i.e. the fit tends to increase the background and to reduce the resolution below 5%. A fit to a single line above a constant background results in a χ^2 of 52 for 9 dof corresponding to a CL $< 10^{-4}$. A three line fit yields an additional line at (147 ± 5.2) MeV with a χ^2 of 5.1 for 12 dof without changing the positions of the two other lines, but the significance for the third line is negligible. Since this third line only shows a $\sim 2.5\sigma$ effect, and some of these events might belong anyhow to the tail of the line at 128 MeV, we regard a two line fit to be more realistic. The results for the different fits are displayed in detail in Table 4.6.

Taking the absolute energy scale into account, we have to scale the peak positions upward by $1/2\%$ yielding (106.1 ± 2.6) MeV and (128.3 ± 1.5) MeV, respectively. These positions are in excellent agreement with the two lower line positions observed in the background subtracted inclusive photon spectrum (see next section and fig. 4.18). Since theoretically the $J=0$ state is predicted to be the lowest 1^3P -state, the two lines observed at 107 MeV and 128 MeV correspond to the transitions via the $J=2$ and $J=1$ χ_b states, respectively.⁺) The measured intensity ratio of both lines corrected for the individual acceptances is $(0.68 \pm 0.24):1$ agreeing reasonably well with theoretically predicted relative intensities of $0.4:1:\sim 0$ for cascade transitions via the 1^3P_2 , 1^3P_1 and 1^3P_0 states. The suppression of the cascade decay via the $J=0$ state is explained by the following arguments:

⁺) To determine the sequence of the 1^3P_J states experimentally one has to measure the angular distributions. However, because of the small statistics and the rather small acceptance of our detector we cannot presently distinguish between the individual distributions.

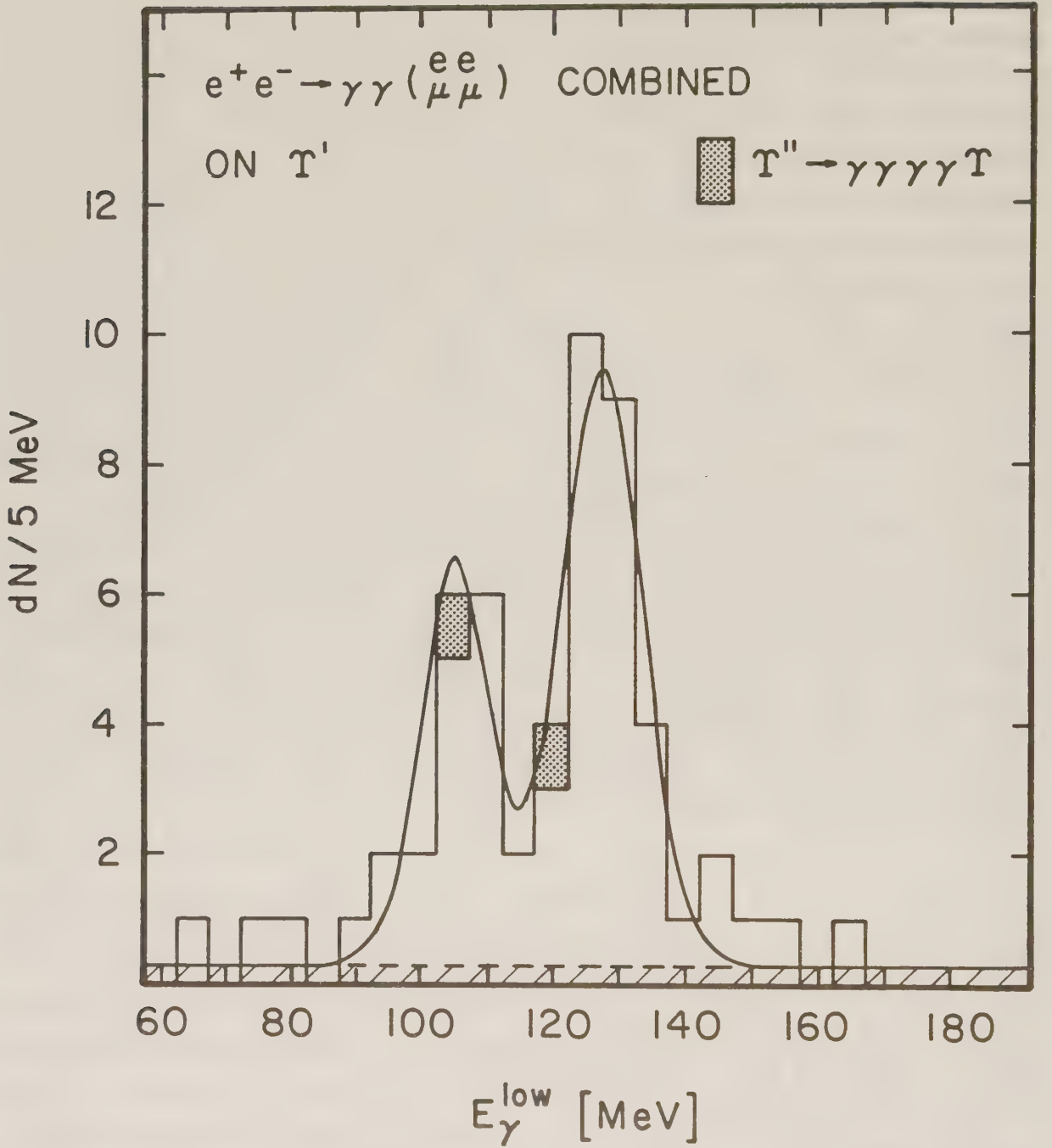


Fig. 4.13 The lower energy photon spectrum for all exclusive $\gamma\gamma\mu^+\mu^-$ or $\gamma\gamma e^+e^-$ decays inside the 2σ bands of the $\gamma\gamma$ correlation plots in figs. 4.7a and 4.7b after constraining the energy sum of both photons to the $T'-T$ mass difference. In addition two events from $T'' \rightarrow \gamma\chi_b' \rightarrow \gamma\gamma T' \rightarrow \gamma\gamma\gamma\chi_b \rightarrow \gamma\gamma\gamma\gamma (T \rightarrow e^+e^-)$ have been included. The solid line shows the fit of two gaussians with widths fixed to the observed energy resolutions over a constant background of 0.25 events/bin.

Table 4.6 Fit parameters for different fit functions to E_{γ}^{low} for λ_b production

fit function	data sample	bckgrnd [events]	E_{peak} [MeV]	σ_{rms} [MeV]	I_{rel}	χ^2/dof	CL [%]
2 gaussians	A	.25	105.5 ± 2.6 127.6 ± 1.5	5.3 6.4	$.58 \pm .19$ 1	6.8/11	>80
2 gaussians	B	.25	105.5 ± 2.6 127.7 ± 1.5	5.3 6.4	$.57 \pm .18$ 1	7.6/11	>75
2 gaussians	A'	.25	105.4 ± 1.9 126.9 ± 1.4	5.3 6.4	$.47 \pm .17$ 1	6.4/12	>85
2 gaussians+ cons.bkgrnd	A ^{+))}	$.76 \pm .3$	107.1 ± 1.4 127.4 ± 1.2	4.2 ± 0.7 5.0 ± 0.8	$.52 \pm .19$ 1	3.6/6	89
3 gaussians	A	.25	105.4 ± 2.8 127.2 ± 1.5 146.7 ± 5.2	5.3 6.4 7.5	$.59 \pm .19$ 1 $.14 \pm .09$	5.1/12	>97
3 gaussians	B	.25	105.4 ± 1.1 127.4 ± 1.5 146.8 ± 5.1	5.3 6.4 7.5	$.57 \pm .19$ 1 $.14 \pm .09$	5.5/12	>92
3 gaussians	A'	.25	105.3 ± 2.0 126.6 ± 1.5 152.2 ± 1.5	5.3 6.4 7.5	$.47 \pm .16$ 1 $.10 \pm .08$	5.1/12	>97
3 gaussians+ cons. bkgrnd	A ^{+))}	$.54 \pm .37$	107.1 ± 1.4 127.3 ± 1.1 145.7 ± 6.1	4.2 ± 0.8 5.0 ± 0.9 6.7 ± 1.1	$.54 \pm .21$ 1 $.11 \pm .10$	3.7/4	>95
1 gaussian	A ^{+))}	.25	120.7 ± 0.6	6.4		52/9	$<10^{-4}$
1 gaussian	B ^{+))}	.25	122.0 ± 0.9	6.4		49.8/10	$<10^{-4}$
1 gaussian	A' ^{+))}	.25	124.0 ± 1.3	6.4		44.5/10	$<10^{-4}$

A:entire data sample consisting of all $\gamma\gamma\mu\mu$, all $\gamma\gamma ee$ and the 2 multiple cascade events

B: $\gamma\gamma ee$ and $\gamma\gamma\mu\mu$ events only

A':entire data sample (A), with binning shifted by 2.5 MeV

^{+))} Background (constant) and resolution are kept as free parameters.

For all other fits background and resolution fixed to the measured values.

- i) Due to the smaller statistical weight $(2J+1)/9$ the E1 transition $\Upsilon' \rightarrow \gamma 1^3P_0$ is already reduced.
- ii) Due to the large annihilation rate $\Gamma_{\text{ann}}(1^3P_0 \rightarrow 2g) \sim 600 \text{ keV}$ [KY 81] the branching ratio for the E1 transition is rather small. By comparison the relative annihilation rates are related by [KY 81]:
 $\Gamma_{\text{ann}}(1^3P_2 \rightarrow 2g) : \Gamma_{\text{ann}}(1^3P_1 \rightarrow gq\bar{q}) : \Gamma_{\text{ann}}(1^3P_0 \rightarrow 2g) \quad \text{as} \quad \sim 3:1:\sim 13.$

IV.2.6 Results from the Inclusive Photon Analysis

To search for χ_b production in the inclusive photon spectrum we have analyzed 230,000 hadronic events collected at the Υ' peak in the same running period, of which 153,000 events are resonance decays.+) A detailed description is given in reference [K1 84]. The hadronic event sample has been selected by the hadronic criteria quoted in section III.3.3 yielding a finding efficiency of $(84 \pm 5)\%$. The signal from $\Upsilon' \rightarrow \gamma \chi_b$ transitions is expected to be on top of a large background since typically 8 charged particles and 8 photons from $4\pi^0$'s are produced per hadronic Υ' decay. However, because of overlaps between two photon showers or a photon with a charged particle, on the average ~ 11 clusters are observed.

Because of the removal of the OSC's, tight selection criteria are necessary to identify photons in such high multiplicity events. We have therefore required clean, well separated showers with characteristic profiles and radial shower development, where each octant is considered independently. This reduces overlaps and rejects minimum ionizing tracks. In order to retain a good energy resolution of 6.4% in the 100 MeV energy range we have considered only photons from the CD, restricting the fiducial volume to $|\delta| \leq 40^\circ$ and $\phi_L \leq 35^\circ$, i.e. 48% of 4π sr. The energies accepted range between 22 MeV and 2200 MeV. The individual photon energies have been determined by adjusting the raw energies obtained from the source calibration by an average correction factor of 1.11. This accounts both for losses due to the inactive material in our detector, neglecting all angular effects, and the 2% scale shift resulting from the exclusive analysis of the hadronic decay mode $\Upsilon' \rightarrow \pi^0 \pi^0 \Upsilon$. The application of tight photon selection criteria results in a low photon finding efficiency of $\sim 13\%$ over the energy range from 80 MeV to 500 MeV. However, the energy resolution is $\sigma/E = 3.6\%/\sqrt{E}(\text{GeV})$. Both energy resolution and photon finding efficiency have

+) For the exclusive and inclusive data analysis the number of hadronic events used for normalization differ slightly due to different selection criteria.

been obtained from MC studies. Photon showers generated with the EGS MC program are randomly superimposed on hadronic events which then are processed through the same photon-finding algorithm. The MC calculated resolution has been further cross-checked by analyzing the monochromatic lines from $1^3P_2 \rightarrow \gamma T$ and $1^3P_1 \rightarrow \gamma T$ as shown in fig. 4.18b and from the energy sum of the four photons from the transition $T' \rightarrow \pi^0 \pi^0 T$ (fig. 4.6).

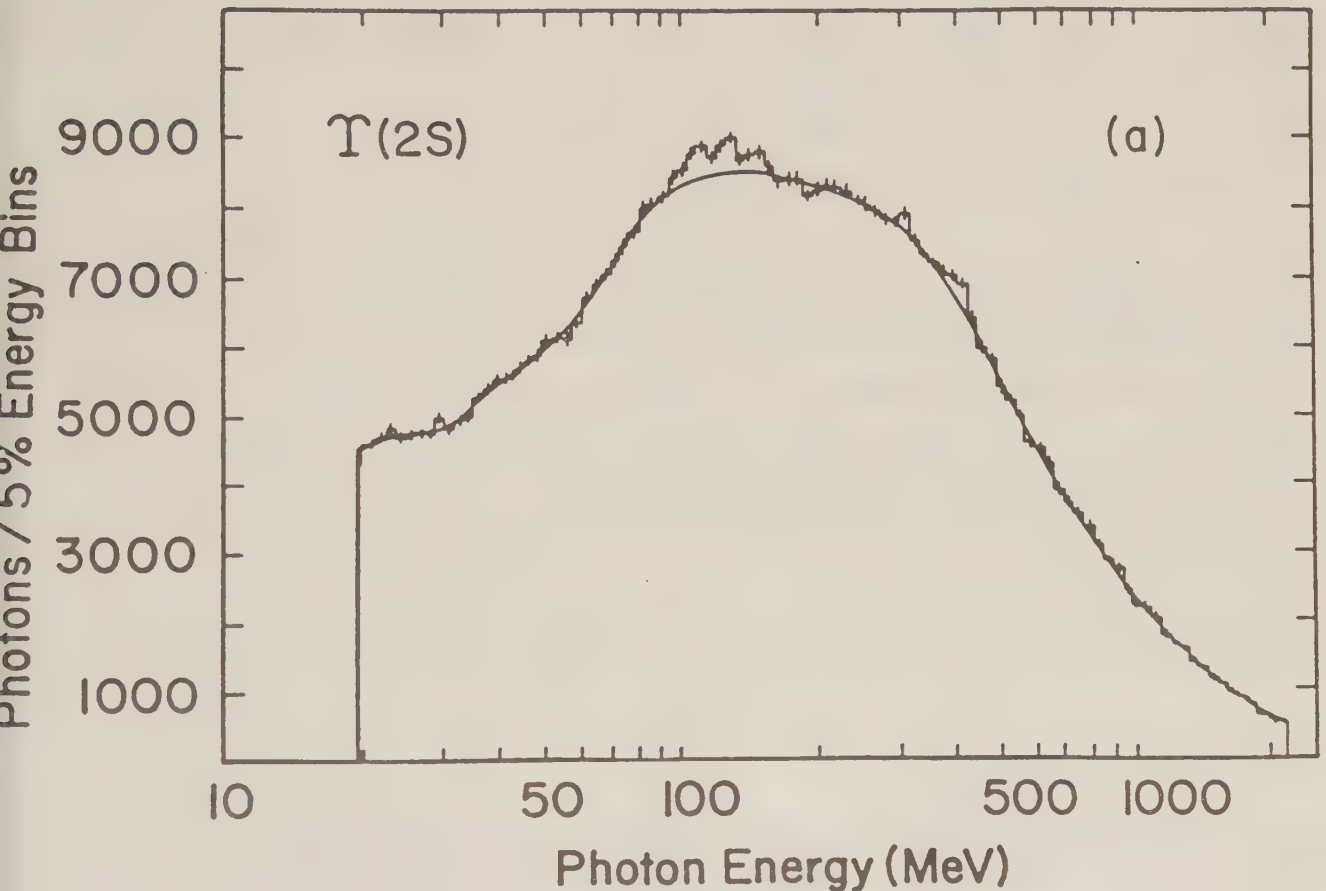


Fig. 4.14 The inclusive photon spectrum observed in hadronic decay modes $T' \rightarrow \gamma + X$. The background curve in the region 65-280 MeV is obtained by fitting a cubic polynomial (background) plus 3 gaussians (signal). For details see text.

Fig. 4.14 shows the inclusive photon spectrum obtained at the T' peak. A prominent excess of photons is visible around 125 MeV together with a smaller but statistically significant excess at ~ 425 MeV, which is not found in the spectra from T decays and continuum events recorded under the same running conditions. This excess is also absent in the spectra from the larger T and continuum samples accumulated during the running period at the T'' , whereas the spectrum from the T'' data also shows some structure around

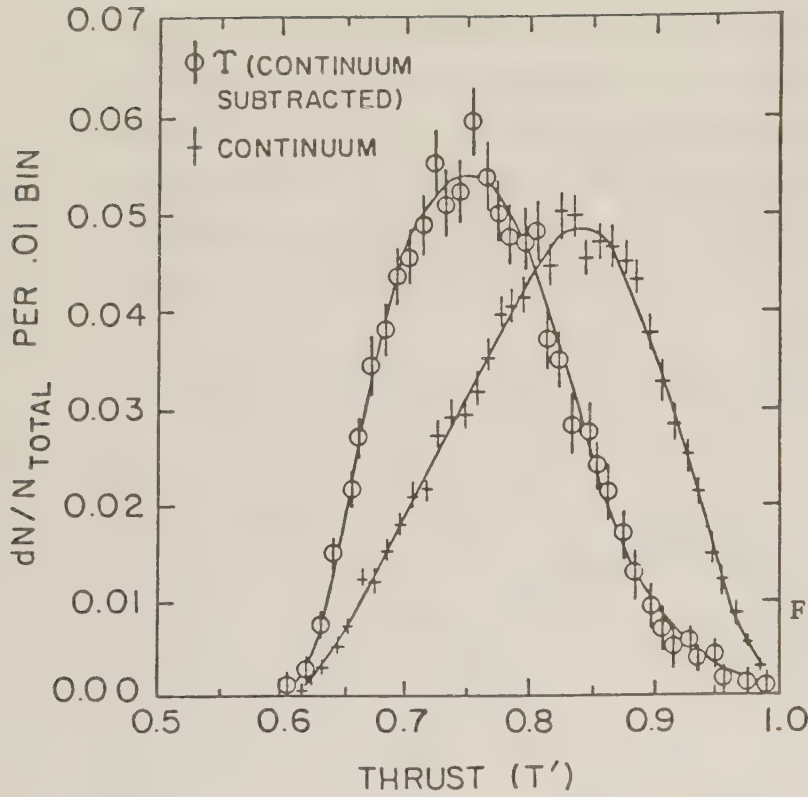


Fig. 4.15 Thrust distributions for hadronic events from the continuum and the continuum-subtracted T data samples.

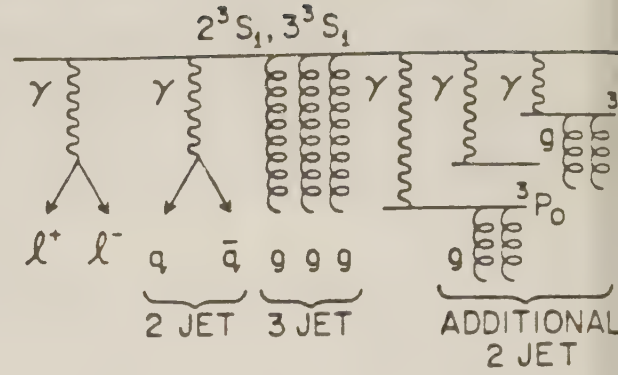


Fig. 4.17 Schematic representation of 2^3S_1 and 3^3S_1 decays, indicating additional 2 jet sources.

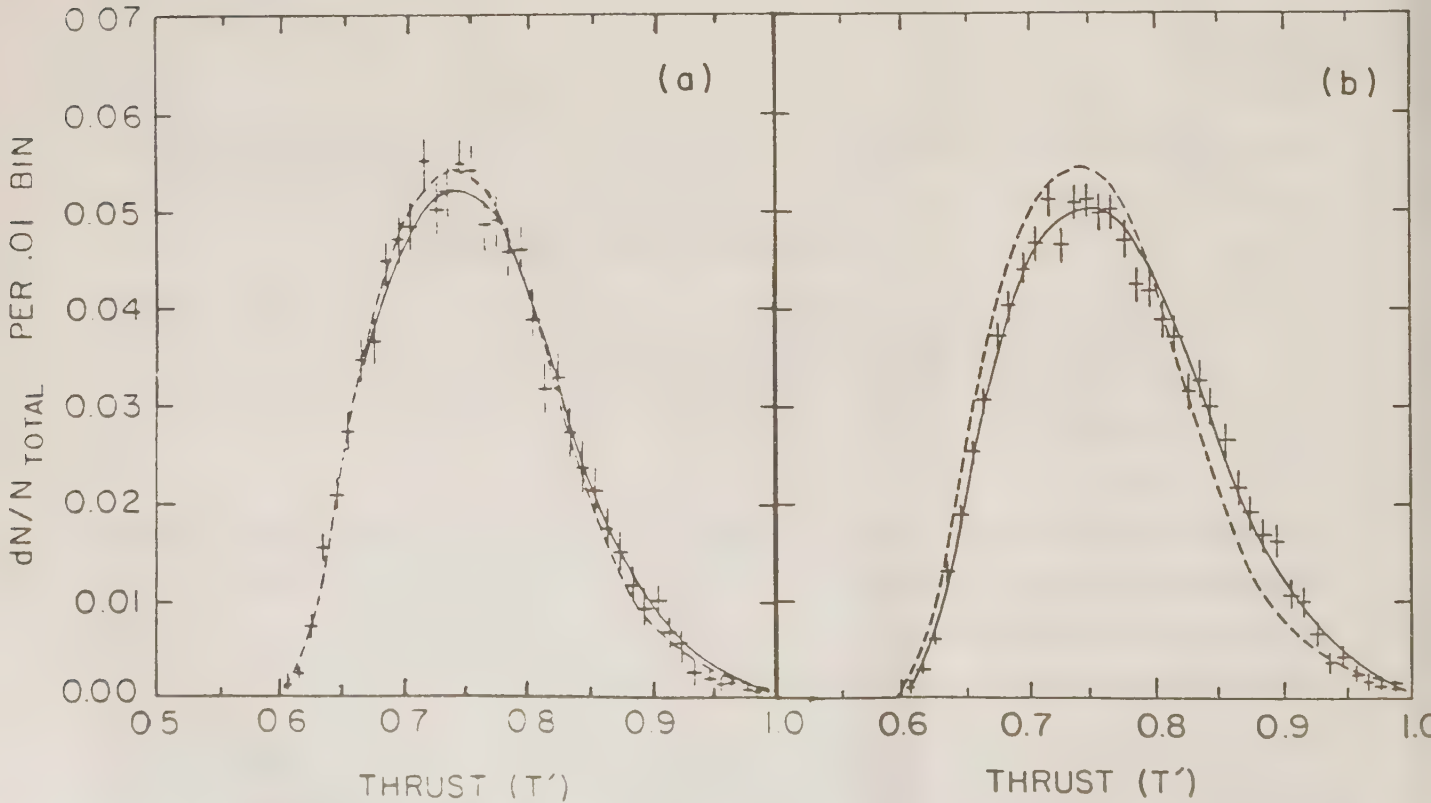


Fig. 4.16 Thrust distribution for hadronic events after continuum subtraction, a) in the T' data sample and b) in the T'' data sample. The dashed curves are a fit to the T data after normalizing equal areas. The solid curves are a fit to a linear combination of T and continuum data.

~100 MeV (compare Section IV.3.6 and figs. 4.33). The natural explanation for the enhancement around 125 MeV and 425 MeV is that photons from the E1 transitions $T' \rightarrow \gamma \lambda_b$ and $\lambda_b \rightarrow \gamma T$ are observed.

The background underlying the signal essentially comes from three different sources:

- i) mainly from two photon decays of light neutral mesons (π^0 's or η 's) produced in the annihilation process of the T' , λ_b or T . (Similar processes also account for the T and continuum spectra).
- ii) to a small fraction (<4%) from photons from the hadronic transition $T' \rightarrow \pi^0 \pi^0 T$ which show a smooth energy distribution between 20 MeV and 420 MeV with a shallow maximum around 175 MeV.
- iii) at low energies (<60 MeV) from 'fake' showers, i.e. energy thrown off from showers and charged particles.

Unfortunately, a π^0 subtraction does not reduce the background substantially. Because of the small photon finding efficiency and imprecisely measured photon directions, the probability of reconstructing π^0 's is rather low. Different methods have been used to model the background in fig. 4.14:

- i) A background spectrum was constructed from a linear combination of the observed spectra for T and continuum data, scaling by the appropriate number of hadronic events. The coefficients (80% T and 20% continuum) were obtained from the linear combination of thrust distributions⁺ for T and continuum data (shown in fig. 4.15) to

⁺) Since the non-magnetic CUSB detector provides no momentum measurements, a planar pseud thrust is defined using the observed calorimeter energies E_i and particle directions $\vec{r}_i$:

$$T' = [\sum_i E_i |\vec{r}_i \cdot \vec{n}|] / \sum_i E_i \quad (4.12)$$

T' is maximized over 32 possible discrete orientations of $\vec{n}$, a unit vector perpendicular to the beam axis centered in each of the 32 NaI sectors. T' can take values from 0.5 to 1.0, where large values correspond to back-to-back events (2 jet events) and small values to spherically distributed events (3 jet events). Fig. 4.15 displays the thrust distributions for continuum data (pure 2 jet like) and continuum subtracted T data (3 jet like except for 11% $q\bar{q}$ admixture due to virtual γ annihilation), showing mean values of 0.8182 ± 0.0006 and 0.7644 ± 0.0009 , respectively. On the other hand, the continuum subtracted thrust distributions for T' and T'' data differ from the corresponding thrust distribution for T data by some additional 2 jet component of $(7 \pm 3)\%$ and $(20 \pm 4)\%$, respectively, as shown in figs. 4.16a,b. This 2 jet excess has been interpreted as evidence for E1 transitions to 3P states—compare fig. 4.17—.

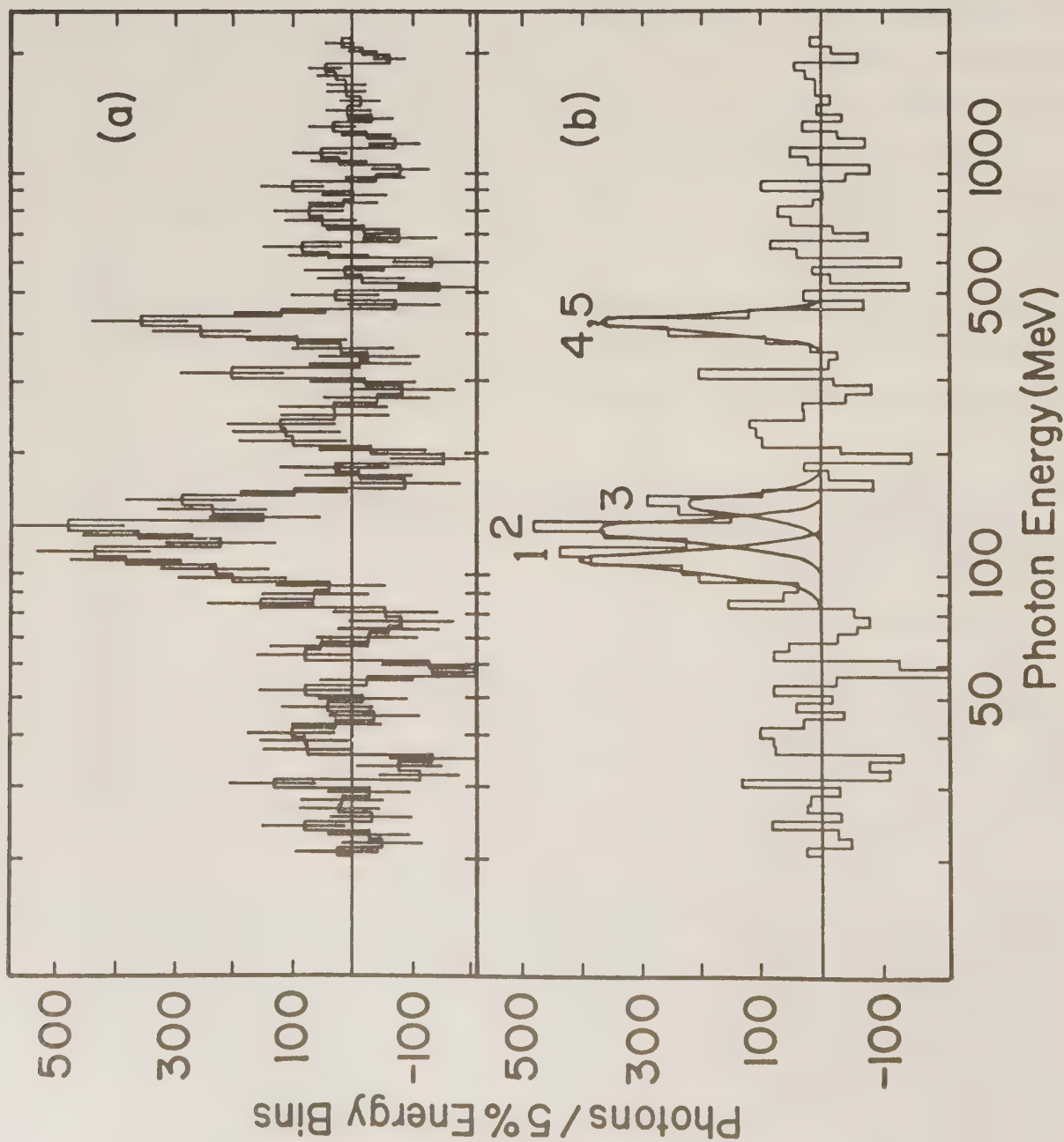


Fig. 4.18 The background subtracted inclusive photon spectrum for T' decays, where a) includes the error bars, and b) shows the fit of four gaussians with widths fixed to the observed resolution. The numbers identify the photon lines as defined in fig. 4.19

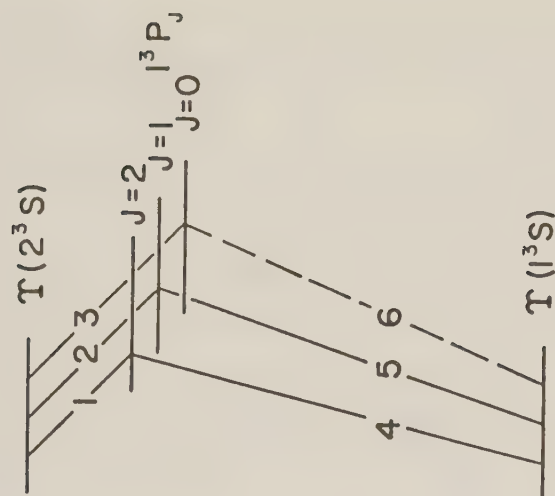


Fig. 4.19 A level diagram for T' photon decays, showing the transitions observed in the background subtracted inclusive photon spectrum. The dashed line indicates the background.

reproduce the observed thrust distribution for the $\mathbf{T}'$ sample (shown in fig. 4.16a) [Pe 82] where a similar fragmentation of quarks and gluons has been assumed. This procedure provides a good background estimate, which is independent of the observed spectrum in fig. 4.14.

ii) The inclusive photon spectrum from the $\mathbf{T}'$ was fitted to a 9th order polynomial excluding the two excess regions around 125 MeV and 425 MeV.

iii) The observed photon spectrum was fitted in the region 65-280 MeV to a cubic polynomial plus 3 gaussians of arbitrary position and area but fixed width of $\sigma/E=6\%$. The fit yielded a χ^2 of 22.6 for 21 dof. The remainder of the spectrum was fitted to a polynomial, matching the value and derivative of the cubic term at 65 and 280 MeV, and excluding 2 bins around 425 MeV. The background curve was then obtained by excluding the gaussians.

All three methods give consistent results, yielding curves that are indistinguishable to the eye. The solid line shown in fig. 4.14 is obtained by the last procedure.

The inclusive photon spectrum after background subtraction is shown in fig. 4.18a. Three resolved lines are observed in the 90-160 MeV region containing 3110 ± 323 excess photons (a 10σ effect) and the narrow peak at ~ 425 MeV containing 833 ± 166 photons (a 4σ effect). Fitting the three lines by gaussians with fixed resolution as described above (see fig. 4.18b) yields peak positions at $(108.2 \pm 0.3 \pm 2)$ MeV, $(128.1 \pm 0.4 \pm 3)$ MeV and $(149.4 \pm 0.7 \pm 5)$ MeV. The peak at ~ 425 MeV is expected to result from the two E1 transitions $1^3P_{1,2} \rightarrow \gamma \mathbf{T}$ as indicated in fig. 4.19. The observed rms spread of $(4.5 \pm 0.4)\%$ is in excellent agreement with MC calculations predicting 4.4%. A gaussian fit yields a peak position at $(427.0 \pm 1.0 \pm 5)$ MeV. Since the splitting of the 1^3P_2 and 1^3P_1 states of ~ 21 MeV is at the same order as the resolution at 425 MeV (19 MeV) the two lines cannot be resolved. To demonstrate that we in fact observe photons from $1^3P_{1,2} \rightarrow \gamma \mathbf{T}$, we have to show the energy sum $E_{\gamma}^{\text{low}} + E_{\gamma}^{\text{high}} + E_{\text{recoil}}$ to be equal to $M_{\mathbf{T}'} - M_{\mathbf{T}}$. Using the predicted intensity ratio of 2:5: ~ 0 for the photon cascades via the $J=2$, $J=1$, and $J=0$ states the energy sum becomes $(108 \times 2 + 128 \times 5)/7 + 427 + 10.5 = 560$ MeV. Considering the large systematics this is consistent with the $\mathbf{T}' - \mathbf{T}$ mass difference of 563.5 MeV.

The line positions are rather stable. A shift of the background curve affects the number of excess photons and therefore branching ratios but does not alter the peak positions considerably. Fig. 4.20 compares the low

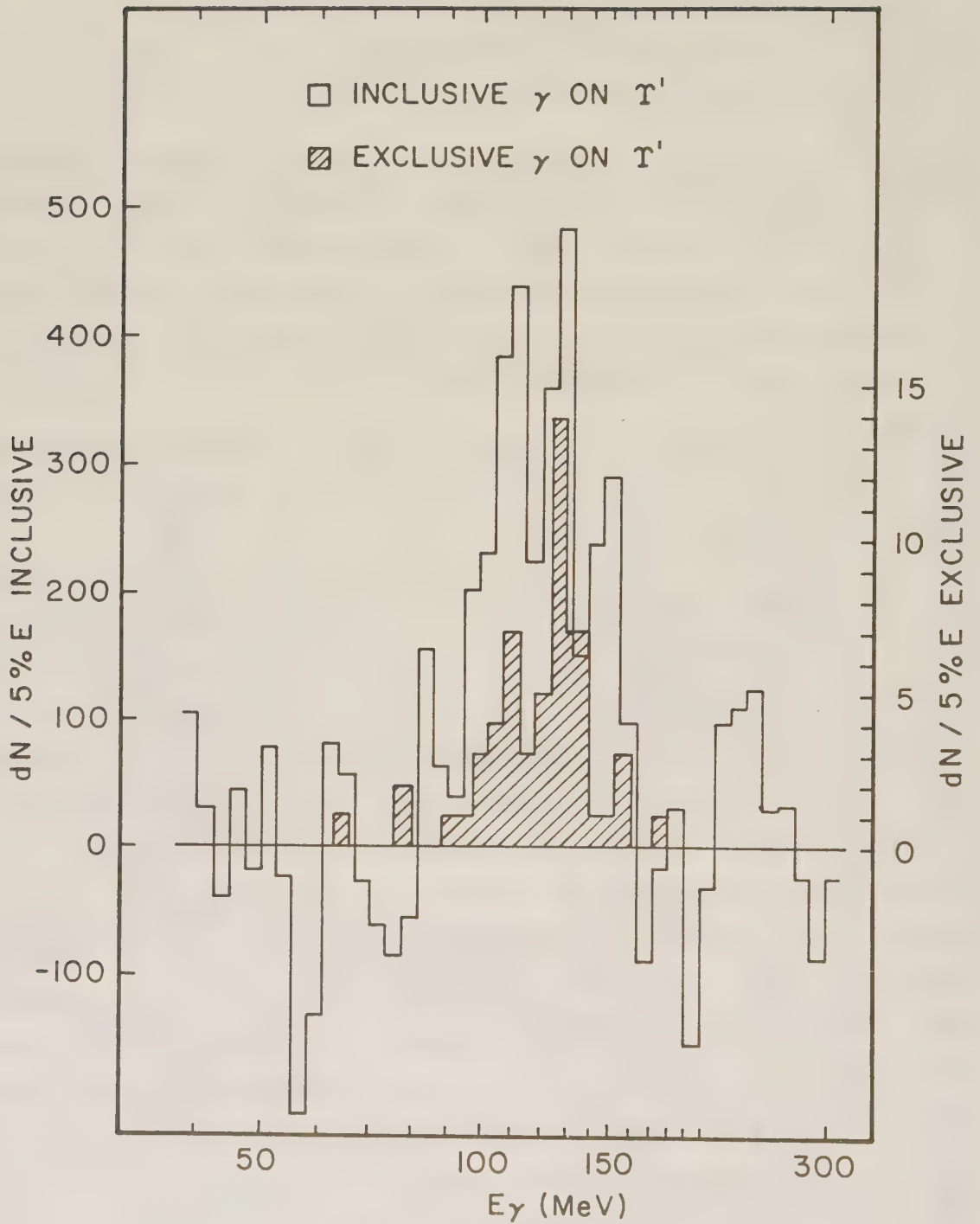


Fig. 4.20 Comparison of the lower energy photon spectrum of the exclusive T' decays shown in fig. 4.13 with the background subtracted inclusive photon spectrum of fig. 4.18a.

energy photon spectrum from the exclusive cascade events with the background subtracted inclusive photon spectrum, showing an excellent agreement for the two lower lines.

IV.2.7 χ_b Masses

The χ_b masses are now unambiguously determined by subtracting E_{γ}^{low} from $M_{\Upsilon'}=10023.5$ MeV and correcting for a recoil of ~ 0.8 MeV. The individual masses obtained both from the inclusive background subtracted photon spectrum and the low energy photon spectrum of the exclusive cascade events are summarized in table 4.7 showing an excellent agreement for the $J=2$ and $J=1$ states. The error bars quoted contain both statistical and systematic uncertainties. The level spacings $\Delta M(1^3P_2-1^3P_1)=(20.9\pm 2.3)$ MeV and $\Delta M(1^3P_1-1^3P_0)=(21.5\pm 5.2)$ MeV are nearly the same. Table 4.7 also shows the weighted χ_b center-of-gravity which is given by:

$$M(^3P_{\text{cog}}) = \frac{2}{\sum_{J=0}} M(^3P_J) \cdot (2J+1) / 9 \quad (4.13)$$

Table 4.7 χ_b masses obtained from the inclusive and exclusive photon analyses

	M(inc) [MeV]	M(exc) [MeV]	$\bar{M}$ [MeV]
1^3P_0	9873 ± 5	-----	9873 ± 5
1^3P_1	9894 ± 3	9894 ± 2	9894 ± 2
1^3P_2	9915 ± 2	9917 ± 3	9915 ± 2
1^3P_{cog}	9903 ± 2	-----	9904 ± 1.5

IV.2.8 Branching Ratios

The Υ' data sample used in the analysis of exclusive $\gamma\gamma$ cascades contains 244,000 hadronic events, which passed the hadronic selection criteria. The portion of continuum underlying the resonance, determined from the total integrated luminosity of 29.6 pb^{-1} and a measured continuum cross section of $(2.74\pm 0.07) \text{ nb}$, is $N_{\text{con}}(\Upsilon')=L\cdot\sigma_{\text{con}}(\Upsilon')=81,000\pm 2,000$ events, thus leaving 163,000 observed hadronic resonance decays. To obtain the total number of Υ' resonance events produced $N_{\text{prod}}(\Upsilon')$ one has to correct the number of observed hadronic events for the hadronic detection efficiency $\sigma_{\text{had}}(\Upsilon')=0.84\pm 0.05$ [Yo 83] and account for all leptonic and semileptonic

decay modes of the Υ' like $\Upsilon' \rightarrow ee$, $\mu\mu$, $\tau\tau$ and $\Upsilon' \rightarrow \pi\pi(\Upsilon \rightarrow \text{lepton pairs})^+)$. Using the values for $B_{\mu\mu}$ from table 2.2, the world average of $BR(\Upsilon' \rightarrow \pi^+\pi^-\Upsilon) = 0.188 \pm 0.01$ and the fractions quoted in the footnote we estimate a correction of $(7 \pm 2)\%$ for the non-hadronic decay modes, which finally gives $N_{\text{prod}}(\Upsilon') = 207,000 \pm 13,000$ events.

The product branching ratio $B_{\gamma\gamma}$ for $\Upsilon' \rightarrow \gamma\chi_b \rightarrow \gamma\gamma\Upsilon$ summed over the intermediate $J=1$ and $J=2$ states can be simply expressed by:

$$B_{\gamma\gamma} = \frac{(N_{\text{obs}} - N_{\text{bg}})}{N_{\text{prod}}(\Upsilon') \cdot B_{\mu\mu}(\Upsilon) \cdot \varepsilon_{2\sigma}} \cdot \left[\frac{f_1}{\varepsilon_{\text{tot}}(J=1)} + \frac{f_2}{\varepsilon_{\text{tot}}(J=2)} \right] \quad (4.14)$$

where

N_{obs} : observed signal of $\gamma\gamma\mu\mu$ and $\gamma\gamma ee$ events in the lower energy photon spectrum (fig.4.13)

N_{bg} : corresponding background contribution in the lower energy photon spectrum

$\varepsilon_{2\sigma}$: Efficiency to observe the photon cascade events inside the 2σ -bands of the $E_{\gamma}^{\text{high}} - E_{\gamma}^{\text{low}}$ correlation plot, i.e. $\varepsilon_{2\sigma} = .954$.

f_1, f_2 : fraction of transitions via $J=1$ and $J=2$ 1^3P_J states

$\varepsilon_{\text{tot}}(J)$: detection efficiencies for cascade transitions via the 1^3P_J state summed over all event categories as given in table 4.5.

Restricting the lower energy photon spectrum to the range $90 \leq E_{\gamma}^{\text{low}} \leq 149$ MeV we find a signal of $N_{\text{obs}} = 47$ events whereas the corresponding background amounts to $N_{\text{bg}} = 2.75$ events. From the observed intensity ratio of $0.57:1:\sim 0$ quoted in table 4.6 we determine the fractions for transitions via the $J=1$ and $J=2$ 1^3P states to be $f_1 = 36\%$ and $f_2 = 64\%$. Using the corresponding detection efficiencies of $\varepsilon_{\text{tot}}(J=1) = .259 \pm .006$ and $\varepsilon_{\text{tot}}(J=2) = .221 \pm .006$ as given in table 4.5 we evaluate for the product branching $B_{\gamma\gamma}$:

$$B_{\gamma\gamma} = \sum_{J=1}^2 BR(\Upsilon' \rightarrow \gamma 1^3P_J) \times BR(1^3P_J \rightarrow \gamma\Upsilon) = (3.2 \pm 0.7 \pm 0.1)\% \quad (4.15)$$

From the fractions $f_J/\varepsilon_{\text{tot}}(J)$ we obtain the product branching for the individual transitions via $J=2$ and $J=1$ χ_b states to be:

⁺) However, some of these decay modes are already partly contained in the hadronic event sample. According to MC studies $(15 \pm 5)\%$ of the τ pairs pass the hadronic selection criteria. About 40% of the $\pi\pi(ee \text{ or } \mu\mu)$, $\sim 70\%$ of $\pi^0\pi^0(ee \text{ or } \mu\mu)$ and nearly all $\pi\pi\tau$ events are contained in the hadronic event sample.

$$\text{BR}(\mathbf{T}' \rightarrow \gamma 1^3\text{P}_2) \times \text{BR}(1^3\text{P}_2 \rightarrow \gamma \mathbf{T}) = (1.3 \pm 0.4)\% \quad (4.16a)$$

$$\text{BR}(\mathbf{T}' \rightarrow \gamma 1^3\text{P}_1) \times \text{BR}(1^3\text{P}_1 \rightarrow \gamma \mathbf{T}) = (1.9 \pm 0.4)\% \quad (4.16b)$$

For the product BR via the J=0 state we deduce an upper limit from the 3 events observed in the energy range $149 \leq E_\gamma^{\text{low}} \leq 175$ MeV. Considering a background portion of 1.25 events and using the event detection efficiency $\varepsilon_{\text{tot}}(J=0) = 0.203 \pm 0.005$ (see table 4.5) we obtain:

$$\text{BR}(\mathbf{T}' \rightarrow \gamma 1^3\text{P}_0) \times \text{BR}(1^3\text{P}_0 \rightarrow \gamma \mathbf{T}) < 0.36\% \quad (90\% \text{ CL}) \quad (4.16c)$$

From the 3110 excess photons around ~125 MeV observed in the inclusive photon spectrum, a photon recovery efficiency of 13%, and the number of hadronic $\mathbf{T}'$ decays we derive a total branching ratio for the E1 transitions $\mathbf{T}' \rightarrow \gamma \chi_b$ of:

$$\sum_{J=0}^3 \text{BR}(\mathbf{T}' \rightarrow \gamma 1^3\text{P}_J) = (15.5 \pm 2.5 [+5-2.5])\% \quad (4.17)$$

The errors in the square brackets indicate systematic uncertainties. From the observed intensity ratio 1.03:1:1.59 for the E1 transitions to the J=2, J=1, and J=0 states we can determine the individual BR's, yielding:

$$\text{BR}(\mathbf{T}' \rightarrow \gamma 1^3\text{P}_2) = (6.1 \pm 1.4)\% \quad (4.18a)$$

$$\text{BR}(\mathbf{T}' \rightarrow \gamma 1^3\text{P}_1) = (5.9 \pm 1.4)\% \quad (4.18b)$$

$$\text{BR}(\mathbf{T}' \rightarrow \gamma 1^3\text{P}_0) = (3.5 \pm 1.4)\% \quad (4.18c)$$

For the signal at ~427 MeV we calculate a product branching fraction of:

$$\sum_{J=1}^2 \text{BR}(\mathbf{T}' \rightarrow \gamma 1^3\text{P}_J) (1^3\text{P}_J \rightarrow \gamma \mathbf{T}) = (4.0 \pm 1 \pm 2)\% \quad (4.19)$$

which is in good agreement with eq. (4.15). Dividing eqs. (4.16a,b) by eqs. (4.18a,b) allows one to determine the BR's for the E1 transitions $1^3\text{P}_{2,1} \rightarrow \gamma \mathbf{T}$, yielding:

$$\text{BR}(1^3\text{P}_2 \rightarrow \gamma \mathbf{T}) = (21 \pm 8)\% \quad (4.20a)$$

$$\text{BR}(1^3\text{P}_1 \rightarrow \gamma \mathbf{T}) = (31 \pm 10)\% \quad (4.20b)$$

From eq. (4.16c) and eq. (4.18c) we can derive an upper limit for the transition $1^3\text{P}_0 \rightarrow \gamma \mathbf{T}$:

$$\text{BR}(1^3\text{P}_0 \rightarrow \gamma \mathbf{T}) < 10\% \quad (90\% \text{ CL}) \quad (4.20c)$$

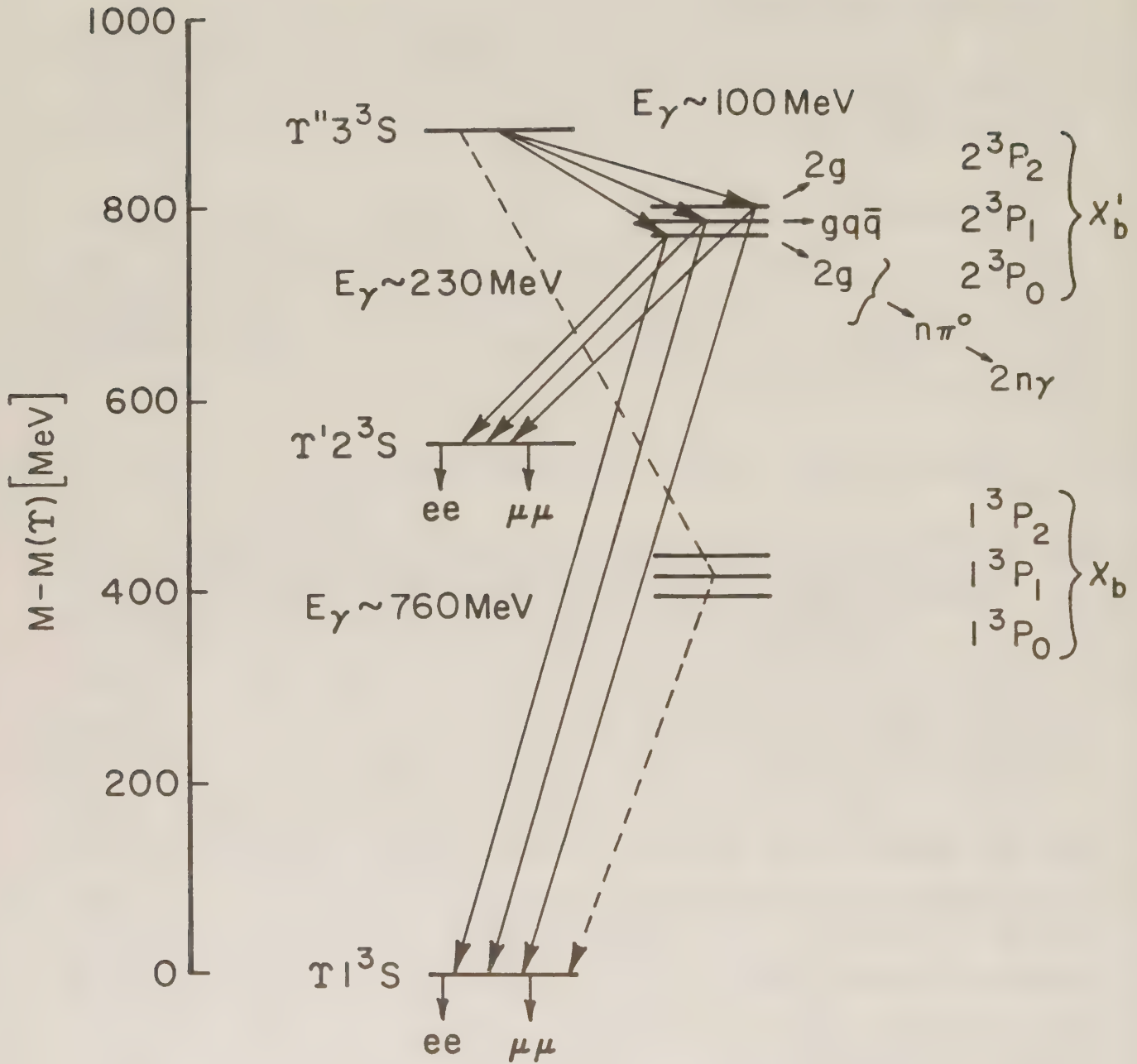


Fig. 4.21 Level diagram showing the individual exclusive cascade decays $\tau'' \rightarrow \gamma 2^3P_J \rightarrow \gamma \gamma \tau' (\tau) \rightarrow \gamma \gamma (\mu^+\mu^-)$ and $\tau'' \rightarrow \gamma 1^3P_J \rightarrow \gamma \gamma \tau \rightarrow \gamma \gamma (\mu^+\mu^-)$. In addition the hadronic decays of the 2^3P_J states are indicated.

IV.3 Photon Cascades from the Transition $T' \rightarrow \gamma\gamma T(T')$

The three photon cascade transitions $T' \rightarrow \gamma\lambda_b \rightarrow \gamma\gamma(T' \text{ or } T)$ and $T' \rightarrow \gamma\lambda_b \rightarrow \gamma\gamma T$ with a subsequent decay of the final T or T' into e^+e^- or $\mu^+\mu^-$ are shown in a level diagram in fig. 4.21. The expected photon energies are $\sim(100,230)$ MeV, $\sim(100,760)$ MeV and $(450,430)$ MeV, respectively. The product branching ratios for the first two reactions are of the order of a few percent. On the other hand, the transition via the λ_b is expected to be suppressed due to a small overlap of the 3^3S_1 and 1^3P_J wave functions [Ty 82].

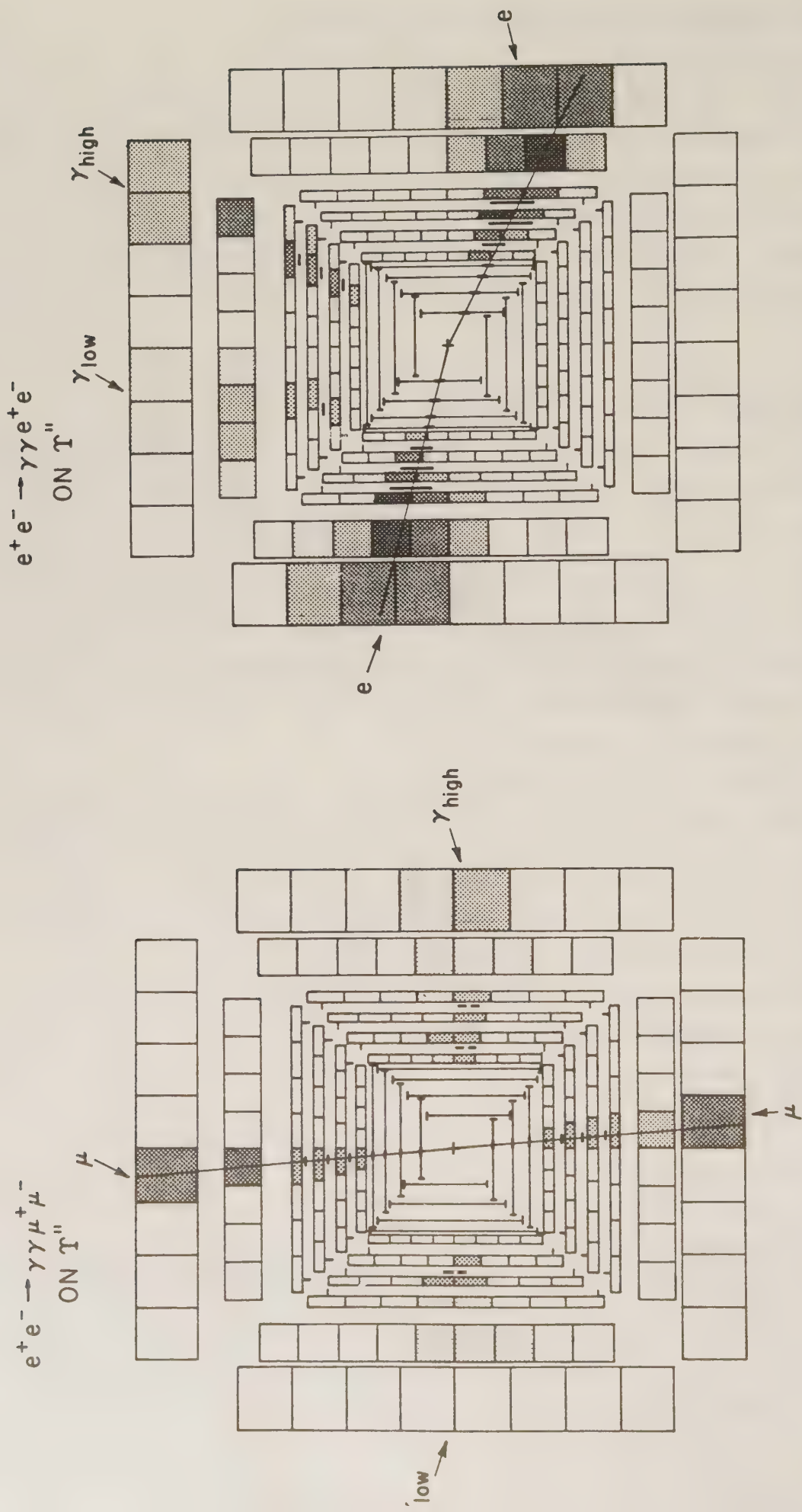
IV.3.1 Selection Criteria for $T' \rightarrow \gamma\gamma(ee \text{ or } \mu\mu)$

The selection criteria are very similar to those for $T' \rightarrow \gamma\gamma T$. Modifications are due to a smaller muon acceptance and different kinematic properties for the $T' \rightarrow \gamma\gamma T(T')$ transitions. Furthermore, we reduce the fiducial volume for photons in the $\gamma\gamma ee$ sample in order to further improve the energy resolution. This is to compensate for the resolution degradation due to the additional inactive material of the OSC's. For the $\gamma\gamma\mu\mu$ sample, however, which is essentially background free, we choose a larger fiducial photon volume to gain sufficient statistics. For completeness the individual criteria are listed below.

For the $\gamma\gamma\mu\mu$ sample we require:

- i) 2 back-to-back ISC tracks, each pointing to a minimum ionizing pattern in the CD. The accepted acollinearity is $\delta_a \leq 15^\circ (8^\circ)$ for $T' \rightarrow \gamma\gamma T(T')^+)$.
- ii) Vertex cut for ISC tracks: $|x| \leq 2.5\text{cm}$, $|y| \leq 2.5\text{cm}$ $|z| \leq 5\text{cm}$
- iii) Muons in the north-south quadrants must penetrate the muon filter.
- iv) Single photon energies: $50 \leq E_\gamma \leq 950$ MeV
and an energy sum: $150 \leq E_\gamma^{\text{low}} + E_\gamma^{\text{high}} \leq 1100$ MeV.
- v) Fiducial volume for photons and muons:
 - for γ in CD: $|\delta| \leq 42^\circ$ and $\phi_L \leq 42^\circ$
 - for γ in EC: $45^\circ \leq |\delta| \leq 59^\circ$
 - for $\mu\mu$: $|\delta| \leq 27.5^\circ$ and $\phi_L \leq 29^\circ$ for top-bottom.
 $|\delta| \leq 30^\circ$ and $\phi_L \leq 30^\circ$ for north-south.
 - At most one photon in the EC's is accepted.
- vi) The cog of photon showers must be separated by ≥ 2 sectors. Photon showers must be separated from μ -tracks by ≥ 1 sector.
- vii) A maximum of one converted γ is accepted, requiring high ionization in the ISC's.

⁺) For $T' \rightarrow \gamma\gamma T(T') \rightarrow \gamma\gamma(\mu\mu \text{ or } ee)$ the maximum acollinearity is $11^\circ (4^\circ)$.



viii) Besides the two photons no other showers or tracks in the CD or EC are allowed.

ix) For each event the unconstrained kinematic fit must give a $\chi^2 < 9.2$ for 2 dof (1% CL).

A typical $\gamma\gamma\mu\mu$ cascade event for the transition $\Upsilon'' \rightarrow \gamma\gamma\Upsilon'$ is displayed in fig. 4.22. The photon energies are $E_\gamma^{\text{low}} = 86$ MeV and $E_\gamma^{\text{high}} = 260$ MeV.

For the $\gamma\gamma ee$ sample the selection criteria are:

- i) 2 back-to-back ISC tracks from the interaction region, each pointing to within $\pm 10^\circ$ to the cog of a large em shower in the CD, or 2 back-to-back em showers in the EC's are required. The accepted acollinearity for $\Upsilon'' \rightarrow \gamma\gamma\Upsilon'$ is $\delta_a \leq 17^\circ (10^\circ)$ in the CD and $\delta_a \leq 20^\circ (15^\circ)$ in the EC's.
- ii) Vertex cut as for $\gamma\gamma\mu\mu$ events.
- iii) For the e^+e^- system we require an energy sum of $E_{ee} \geq 8$ GeV (3.5 GeV) for well-contained electrons (electrons near edges) and $E_{ee} \geq 2$ GeV in the EC's.
- iv) Both photons have to be in the CD, allowing no additional showers or tracks in the CD or EC's.
- v) Single photon energies: $50 \leq E_\gamma \leq 950$ MeV
and an energy sum: $50 \leq E_\gamma^{\text{low}} + E_\gamma^{\text{high}} \leq 1100$ MeV.
- vi) Fiducial volume for photons and electrons:
 - for γ : $|\delta| \leq 40^\circ$ and $\phi_L \leq 40^\circ$
 - for ee in CD: $|\delta| \leq 42^\circ$ and $\phi_L \leq 42.5^\circ$
 - for ee in EC: $45^\circ \leq |\delta| \leq 68^\circ$
- vii) The cog of both photon showers must be separated by ≥ 2 sectors. Similarly, each photon shower cog has to be separated from the electron track by ≥ 3 sectors. To reduce double Bremsstrahlung of Bhabha scatters, we require in addition for at least one photon a γ -e separation of at least 45° .
- viii) A maximum of one converted γ is accepted, requiring high ionization in the ISC's (more than twice minimum ionization).
- ix) For each event the unconstrained kinematic fit must give a $\chi^2 < 13$ for 4 dof.

Fig. 4.23 shows a typical candidate for the transition $\Upsilon'' \rightarrow \gamma\gamma\Upsilon' \rightarrow \gamma\gamma ee$, observing two electrons with an invariant mass $M_{ee} = 9.5$ GeV and two photons with energies $E_\gamma^{\text{low}} = 95$ MeV and $E_\gamma^{\text{high}} = 720$ MeV.

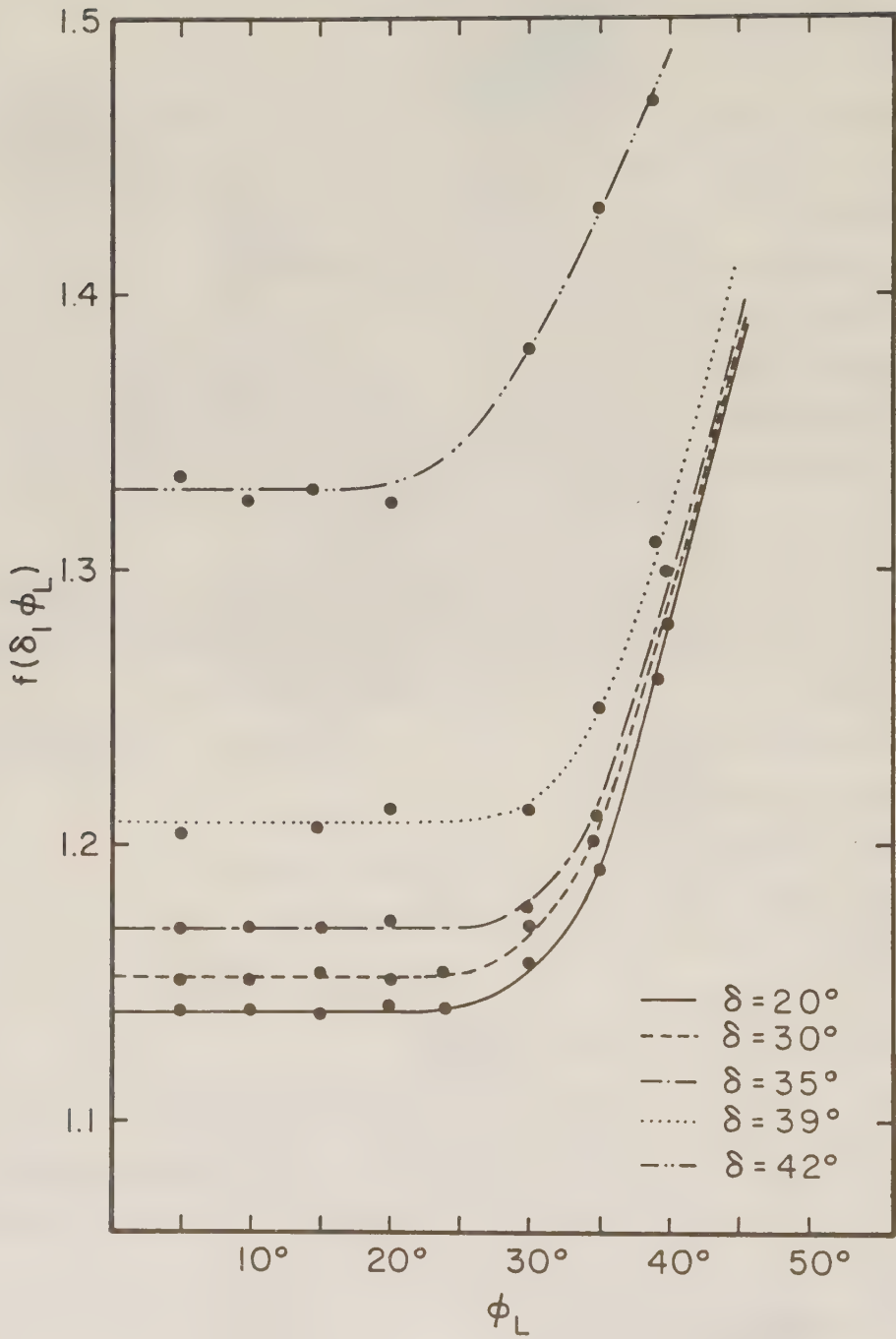


Fig. 4.24 Energy correction factors for photon showers in the central detector including outer strip chambers versus the local azimuth angle ϕ_L for different projected dip angles. The data shown are obtained from a Monte Carlo simulation, the curve is an interpolation between the generated data.

IV.3.2 Determination of Photon Energies

The procedure to determine the energies of photon showers is essentially the same as that discussed in Section IV.2.2. The raw shower energies are corrected by angle-dependent factors $f(\delta, \phi_L)$ obtained from MC studies to compensate for losses in the inactive material and shower leakage at the edges. However, due to the OSC's interleaved between the radial NaI layers the corrections are larger. For angles of $|\delta| \leq 20^\circ$ and $\phi_L \leq 25^\circ$ we determine a 14% correction as shown in fig. 4.24. The corresponding rms resolution is 6.5% at $E_i = 100$ MeV. Near quadrant boundaries or the CD-EC junctions $f(\delta, \phi_L)$ increases rapidly, yielding, for example, a 35% correction with an rms spread of 17% at $|\delta| = 40^\circ$ and $\phi_L = 40^\circ$. These corrections have been obtained for an initial energy of 100 MeV, but in the energy range between 100 MeV and 800 MeV no significant energy dependence has been observed. The energy dependence of the rms resolution can be approximated by $\sigma_E/E = 3.9\%/\sqrt{E_i}(\text{GeV})$ neglecting leakage effects at large angles. For the exclusive $\gamma\gamma$ cascade candidates we determine for 100 MeV photons an average resolution of $\sim 7\%$. For EC photons the correction factors remain unchanged.

IV.3.3 Absolute Calibration and Energy Resolution

To cross-check both the absolute energy scale and resolution for photons in the 100 MeV energy range we again have used the 4 photons from the exclusive hadronic transitions $\Upsilon'' \rightarrow \pi^0 \pi^0 \Upsilon(\Upsilon') \rightarrow \gamma\gamma\gamma\gamma(ee \text{ or } \mu\mu)$. However, the statistics for such events is much lower because of a smaller luminosity, a worse resonance to continuum ratio⁺) and smaller branching fractions $\text{BR}(\Upsilon'' \rightarrow \pi^0 \pi^0 \Upsilon) \simeq 2.4\%$ and $\text{BR}(\Upsilon'' \rightarrow \pi^0 \pi^0 \Upsilon') \simeq 1.5\%$ [Ms 82]. To improve statistics we have selected all $\gamma\gamma\gamma\gamma(ee \text{ or } \mu\mu)$ events with at least 3 out of the 4 photons located in the CD. Requiring that the photons fit two π^0 's within 3 standard deviations we have found 13 (7) candidates for $\Upsilon'' \rightarrow \pi^0 \pi^0 \Upsilon(\Upsilon')$. In addition, we have also included the two events from the multiple cascade transition $\Upsilon'' \rightarrow \gamma\chi_b' \rightarrow \gamma\gamma\Upsilon'' \rightarrow \gamma\gamma\gamma\chi_b \rightarrow \gamma\gamma\gamma\gamma\Upsilon$. Fig. 4.25 shows the distributions for the energy sum of all four photons. The solid curves represent a gaussian with the predicted rms error. The spectra peak at (333 ± 6) MeV and (880 ± 10) MeV, respectively. This is in excellent agreement with expected positions at 331 MeV and 875 MeV, calculated by using the mass differences $M_{\Upsilon''} - M_{\Upsilon} = 332$ MeV, $M_{\Upsilon''} - M_{\Upsilon'} = 895.3$ MeV and the

⁺) At the Υ'' peak the ratio of resonance to continuum is 54% to 46%. Since the luminosity is only 15 nb^{-1} we have accumulated $\sim 1/3$ produced Υ'' resonance events compared to Υ' resonance events.

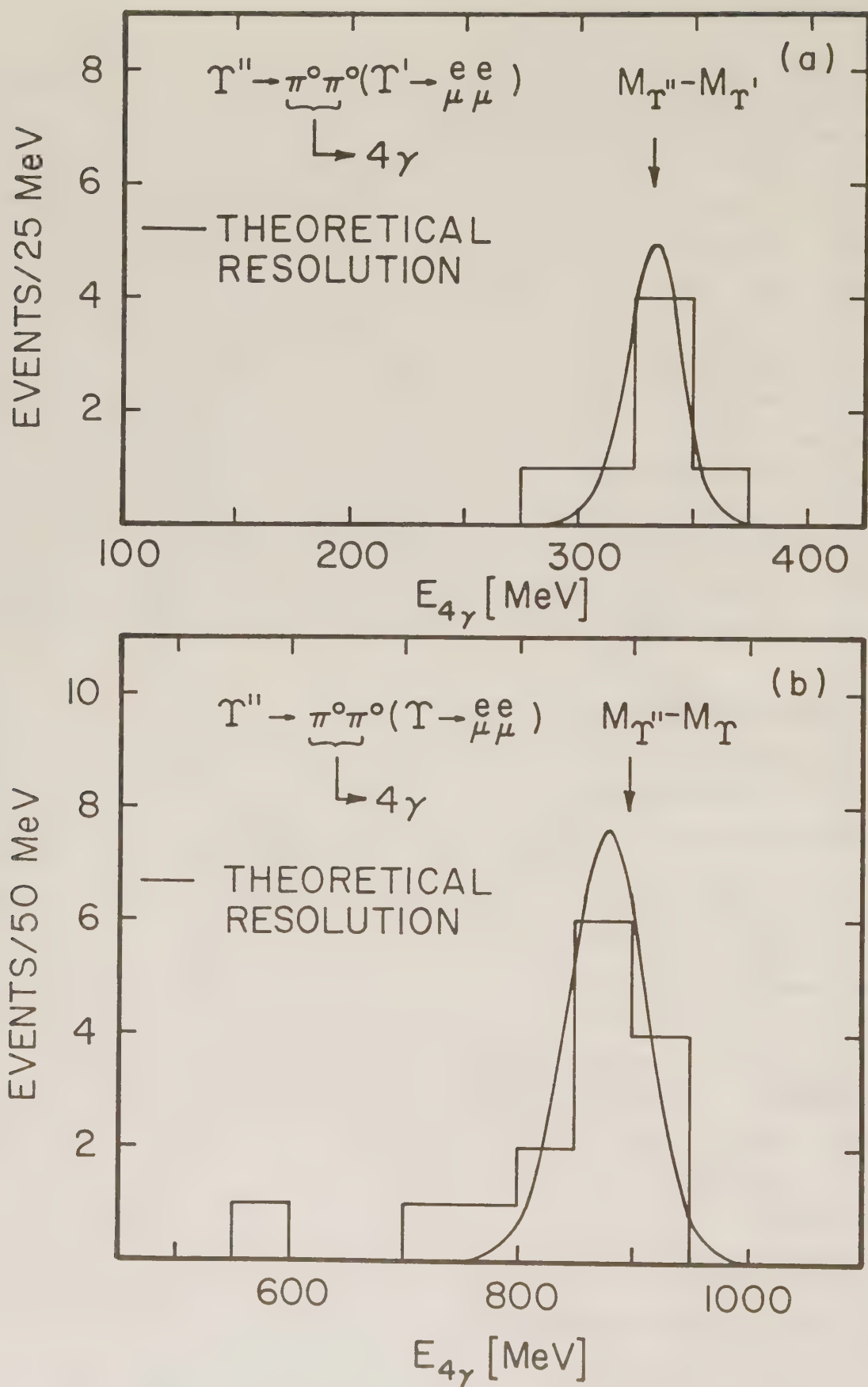


Fig. 4.25 Spectrum of the energy sum of the four photons for
a) $T'' \rightarrow \pi^0 \pi^0 T' \rightarrow \gamma \gamma \gamma \gamma (\mu^+ \mu^- \text{ or } e^+ e^- \text{ decays,}$
b) $T'' \rightarrow \pi^0 \pi^0 T \rightarrow \gamma \gamma \gamma \gamma (\mu^+ \mu^- \text{ or } e^+ e^- \text{ decays.}$
The arrows indicate the energy differences $T'' - T'$ and $T'' - T$.
The solid lines represent gaussians with the predicted rms error
from Monte Carlo calculations.

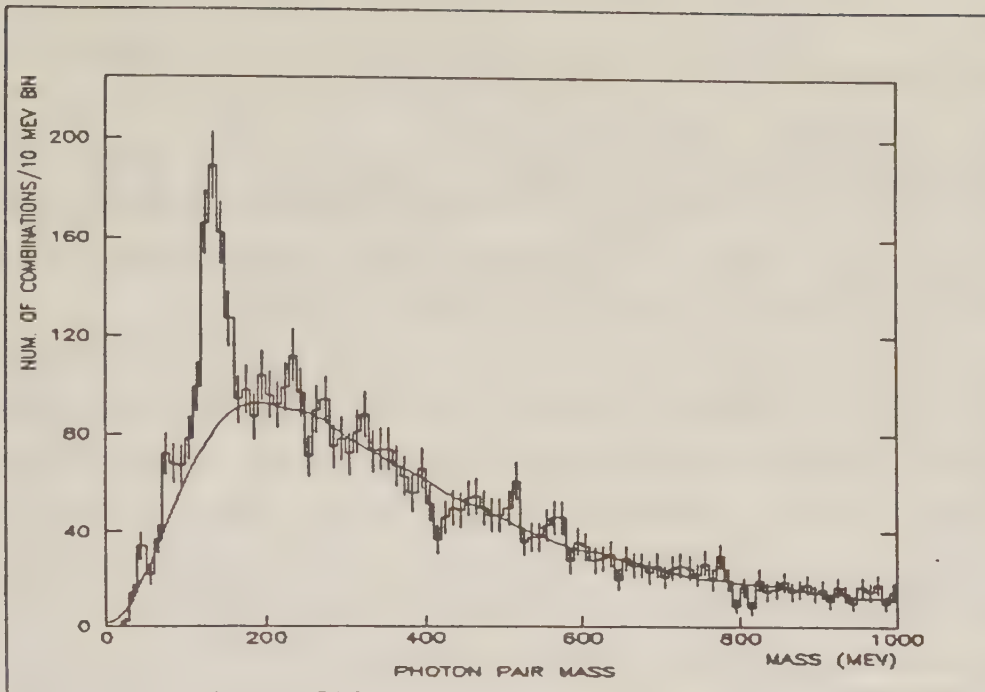


Fig. 4.26a Diphoton mass spectrum at the T'' .

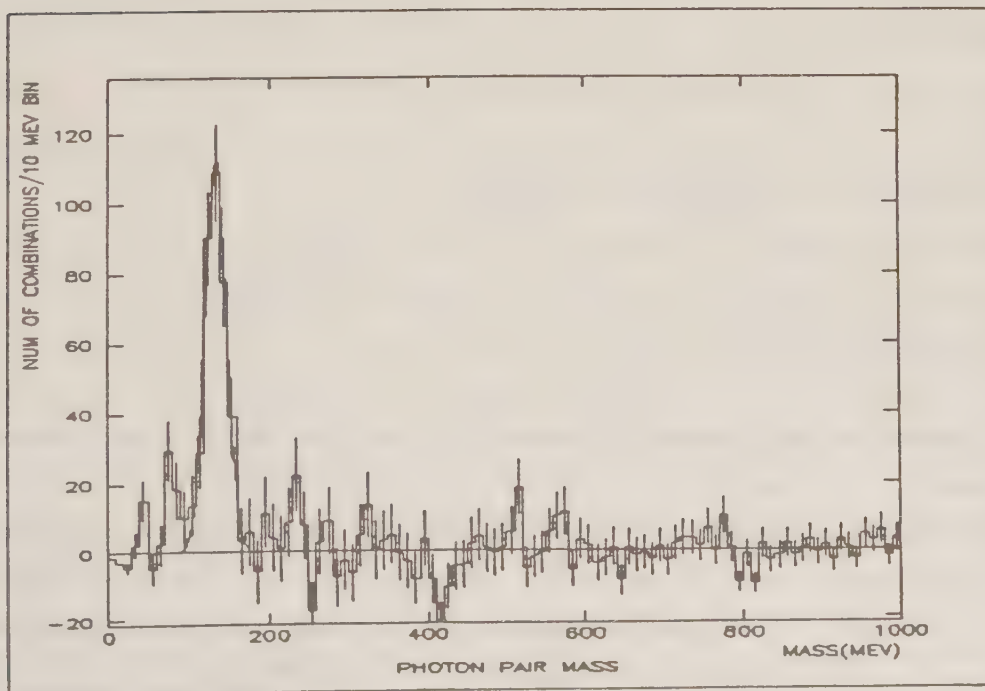


Fig. 4.26b Background subtracted di-photon mass spectrum at the T'' . The solid line represents a fit to a gaussian.

average recoil energy of the Υ or Υ' [Ms 83]. We therefore conclude a systematic uncertainty in the absolute scale of less than 1%.

The observed energy sum spectra have an rms spread of $\sigma_E=8.6$ MeV for $\Upsilon'' \rightarrow \pi^0 \pi^0 \Upsilon'$ and $\sigma_E=34.9$ MeV for $\Upsilon'' \rightarrow \pi^0 \pi^0 \Upsilon$. In comparison the expected resolutions are 12 MeV and 34 MeV, respectively. Considering the uncertainties from low statistics, the energy dependence of the resolution and the larger rms errors for EC photons, this agrees perfectly with the calculated 7% rms spread for exclusive 100 MeV photons.

We have also reconstructed π^0 's from photons in hadronic events, using both data from Υ'' and Υ decays [Hn 83]. The resulting two photon invariant mass spectrum for the Υ'' data is shown in fig. 4.26a. The solid curve is a background estimate obtained by combining two photons from different events using the same selection criteria. The background subtracted spectrum, shown in fig. 4.26b, is fitted by a gaussian curve, keeping peak position, width, and height as free parameters. The fit yields a peak position at (135 ± 1) MeV. In a similar way we obtain a peak position of (132 ± 1) MeV for the invariant mass spectrum from π^0 's of Υ decays confirming that systematic uncertainties in the absolute energy scale are small. The resolution for both spectra is 19.4 MeV and 17.4 MeV, respectively. This is qualitatively in agreement with our single photon resolution. However, a direct comparison is difficult because of systematic uncertainties in the background subtraction, uncertainties in the measurement of photon directions and a very low π^0 reconstruction efficiency.

IV.3.4 Acceptance and Detection Efficiency

The acceptances and detection efficiencies for the $\Upsilon'' \rightarrow \gamma\gamma \Upsilon(\Upsilon')$ transitions are determined by the MC simulation described in IV.2.4 using the corresponding fiducial and overlap cuts of our selection criteria. Table 4.8 summarizes the results for a_j and ϵ_j for each event category. The trigger, scanning and 2 photon finding efficiencies, also listed in table 4.8, are obtained in a similar way as those discussed in section IV.2.4. In the $\mu^+\mu^-$ pair trigger efficiencies a factor of 0.95 is included to account for a reduced operation time of the muon counters during the Υ'' data taking period. Further, a slightly smaller $\mu^+\mu^-$ pair trigger efficiency is determined for $\Upsilon'' \rightarrow \gamma\gamma(\Upsilon \rightarrow \mu\mu)$ than for $\Upsilon'' \rightarrow \gamma\gamma(\Upsilon' \rightarrow \mu\mu)$ since losses at the edges of the muon counters or between adjacent counters are larger for the less collinear muons from the 3S-1S transitions.

Table 4.8 Acceptances and efficiencies for $T' \rightarrow \gamma\gamma T(T')$

	ee $\gamma\gamma$ ee in CD	ee $\gamma\gamma$ ee in EC	$\mu\mu\gamma\gamma$ $\gamma\gamma$ in CD	$\mu\mu\gamma\gamma$ one γ in EC	sum over all categories
α_0	.098 $\pm$.001	.036 $\pm$.001	.071 $\pm$.001	.037 $\pm$.001	.242 $\pm$.002
ϵ_0 (3S-2S)	.090 $\pm$.003	.032 $\pm$.002	.061 $\pm$.002	.028 $\pm$.003	.211 $\pm$.005
ϵ_0 (3S-1S)	.090 $\pm$.003	.032 $\pm$.002	.055 $\pm$.002	.025 $\pm$.003	.202 $\pm$.005
α_1	.120 $\pm$.001	.052 $\pm$.001	.083 $\pm$.001	.035 $\pm$.001	.290 $\pm$.002
ϵ_1 (3S-2S)	.111 $\pm$.004	.046 $\pm$.003	.072 $\pm$.002	.027 $\pm$.003	.256 $\pm$.006
ϵ_1 (3S-1S)	.111 $\pm$.004	.046 $\pm$.003	.064 $\pm$.002	.025 $\pm$.003	.246 $\pm$.006
α_2	.103 $\pm$.001	.047 $\pm$.001	.072 $\pm$.001	.035 $\pm$.001	.257 $\pm$.002
ϵ_2 (3S-2S)	.095 $\pm$.003	.042 $\pm$.003	.062 $\pm$.002	.027 $\pm$.003	.226 $\pm$.006
ϵ_2 (3S-1S)	.095 $\pm$.003	.042 $\pm$.003	.055 $\pm$.002	.024 $\pm$.003	.216 $\pm$.006
η_{tr} (3S-2S)	.97 $\pm$.01	.96 $\pm$.02 ⁺)	.90 $\pm$.02 ⁺⁺)	.90 $\pm$.02 ⁺⁺)	
η_{tr} (3S-1S)	.97 $\pm$.01	.96 $\pm$.02 ⁺)	.80 $\pm$.02 ⁺⁺)	.80 $\pm$.02 ⁺⁺)	
η_{sc}	.98 $\pm$.02	.94 $\pm$.05	.98 $\pm$.01	.90 $\pm$.10	
$\eta_{\gamma\gamma}$	.97 $\pm$.01	.98 $\pm$.01	.98 $\pm$.01	.95 $\pm$.04	

$\eta_{\gamma\gamma}$ includes the probability that both photons are separated by $<45^\circ$ from both the e^+ and e^- showers.

⁺) These numbers include a factor of .97 accounting for runs which could not be used in the analysis because of ADC problems in the EC's.

⁺⁺) These numbers include a factor of .95 accounting for the smaller $\mu\mu X$ data set since the μ -pair trigger was not working at the beginning of the 3S running period.

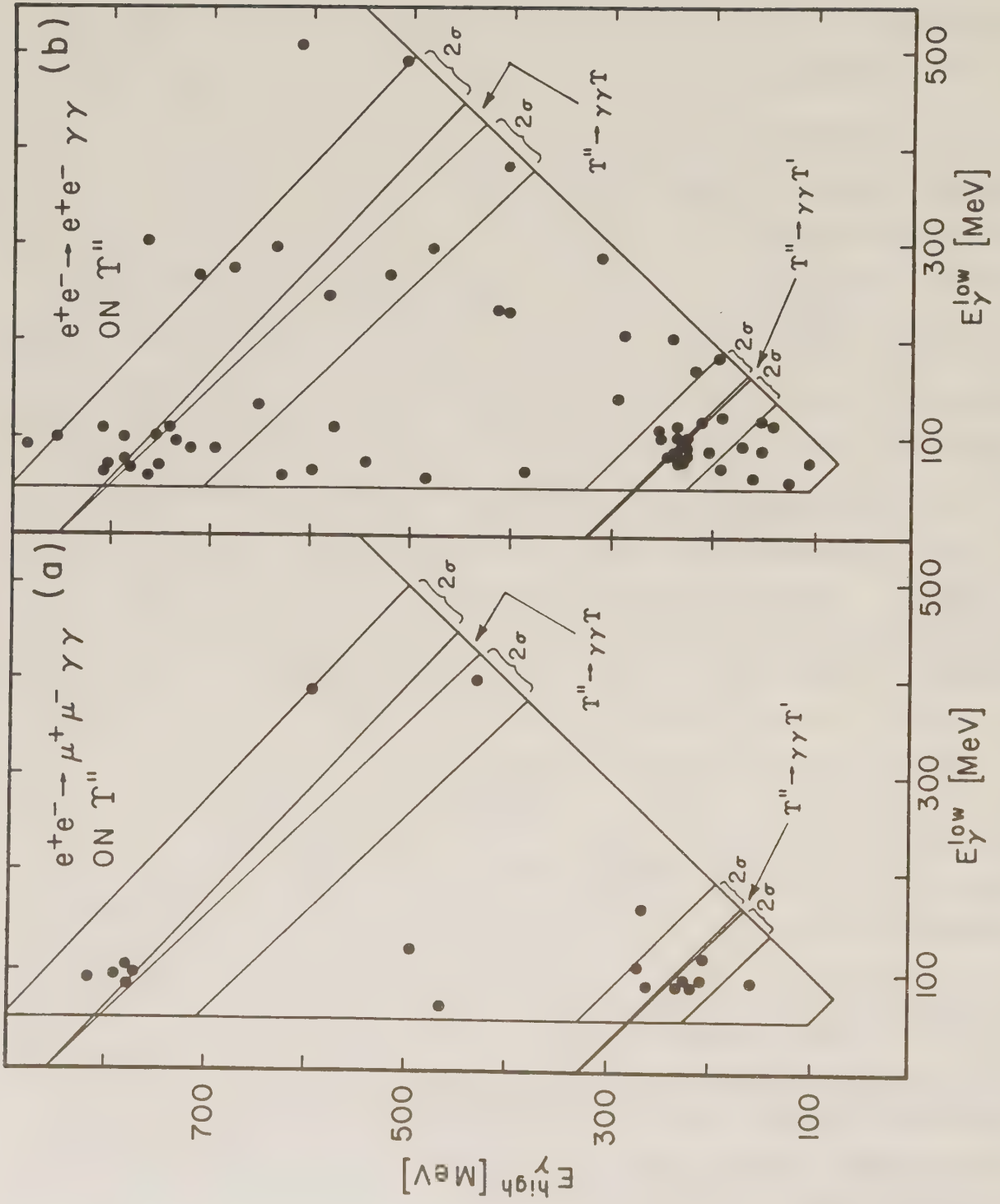


Fig. 4.27 Scatter plot of the higher versus the lower energy photon
a) from $\tau'' \rightarrow \gamma\gamma\mu^+\mu^-$, b) from $\tau'' \rightarrow \gamma\gamma e^+e^-$.

From the angular distribution W_1 we determine the geometric acceptance for lepton pairs inside our fiducial volume to be 30% for $\mu^+\mu^-$, and 58% (25%) for e^+e^- in the CD(EC's). The acceptances for single photons from the cascade transitions via the $J=1$ χ_b' state are 59% (52%) and 11% (12%) for γ_{low} (γ_{high}) in the CD and EC's, respectively. This leads to a total detection efficiency of $\varepsilon_1(\gamma\gamma ee)=16\%$ and $\varepsilon_2(\gamma\gamma ee)=14\%$ for cascades in the $\gamma\gamma ee$ sample. For cascades from the 3S-2S (3S-1S) transitions in the $\gamma\gamma\mu\mu$ sample we determine $\varepsilon_1(\gamma\gamma\mu\mu)=10\%$ (9%) and $\varepsilon_2(\gamma\gamma\mu\mu)=9\%$ (8%).

IV.3.5 Results on the Exclusive Decays $\Upsilon'' \rightarrow \gamma\gamma(ee \text{ or } \mu\mu)$

IV.3.5.1 Signal for χ_b' Production in the $\gamma\gamma$ Correlation Plot

Figs. 4.27a,b show the scatter plots of the higher energy photon versus the lower energy photon for the $\gamma\gamma\mu\mu$ and $\gamma\gamma ee$ samples selected by the handscan, where events with e^+e^- in the CD and EC's have been combined. The region for the transitions $\Upsilon'' \rightarrow \gamma\gamma\Upsilon$ and $\Upsilon'' \rightarrow \gamma\gamma\Upsilon'$ corrected for the $\Upsilon(\Upsilon')$ recoil including Doppler broadening is indicated by the solid lines. The dashed lines again show the $\pm 2\sigma$ limits of our energy resolution, i.e. ± 34 MeV for the 3S-2S and ± 101 MeV for the 3S-1S transition. In both samples two pronounced clusters are visible. In the $\gamma\gamma ee(\gamma\gamma\mu\mu)$ sample, which contains a total of 66 (18) events, 15 (5) candidates cluster at $(E_{\gamma}^{\text{low}}, E_{\gamma}^{\text{high}}) \sim (100, 760)$ MeV and 14 (7) at $(E_{\gamma}^{\text{low}}, E_{\gamma}^{\text{high}}) \sim (100, 230)$ MeV. The natural explanation for these enhancements is that these events result from radiative cascade decays via intermediate χ_b' production. For comparison fig. 4.28 shows a three dimensional plot ('Manhattan plot') of both Υ and Υ' data sets combining all $\gamma\gamma\mu\mu$ and $\gamma\gamma ee$ events. The individual transitions are clearly visible. It should be noted that the $\gamma\gamma\mu\mu$ sample in fig. 4.27a is essentially background free. The two events inside the 2σ -bands around $(E_{\gamma}^{\text{low}}, E_{\gamma}^{\text{high}}) \sim (450, 450)$ MeV are possible candidates for the transition $\Upsilon'' \rightarrow \gamma\chi_b' \rightarrow \gamma\gamma\Upsilon$. In the $\gamma\gamma ee$ sample we observe another 2 such events. To demonstrate further that we indeed observe photon transitions to the 2S and 1S state, fig. 4.29 shows the spectrum of the energy sum $E_{\gamma}^{\text{low}} + E_{\gamma}^{\text{high}}$ for all events in figs. 4.27a,b. Two pronounced peaks at (328.2 ± 4.9) MeV and (862.1 ± 9.7) MeV are visible. This is in perfect agreement with the expected positions of 329 MeV and 864 MeV including correction factors for the $\Upsilon(\Upsilon')$ recoil and Doppler broadening⁺).

⁺) For the 3S-1S (3S-2S) transition at $E_{\gamma}^{\text{low}}=100$ MeV the Doppler broadening is 15 (4.5) MeV. The maximum recoil (both photons parallel) is 39 (5) MeV.

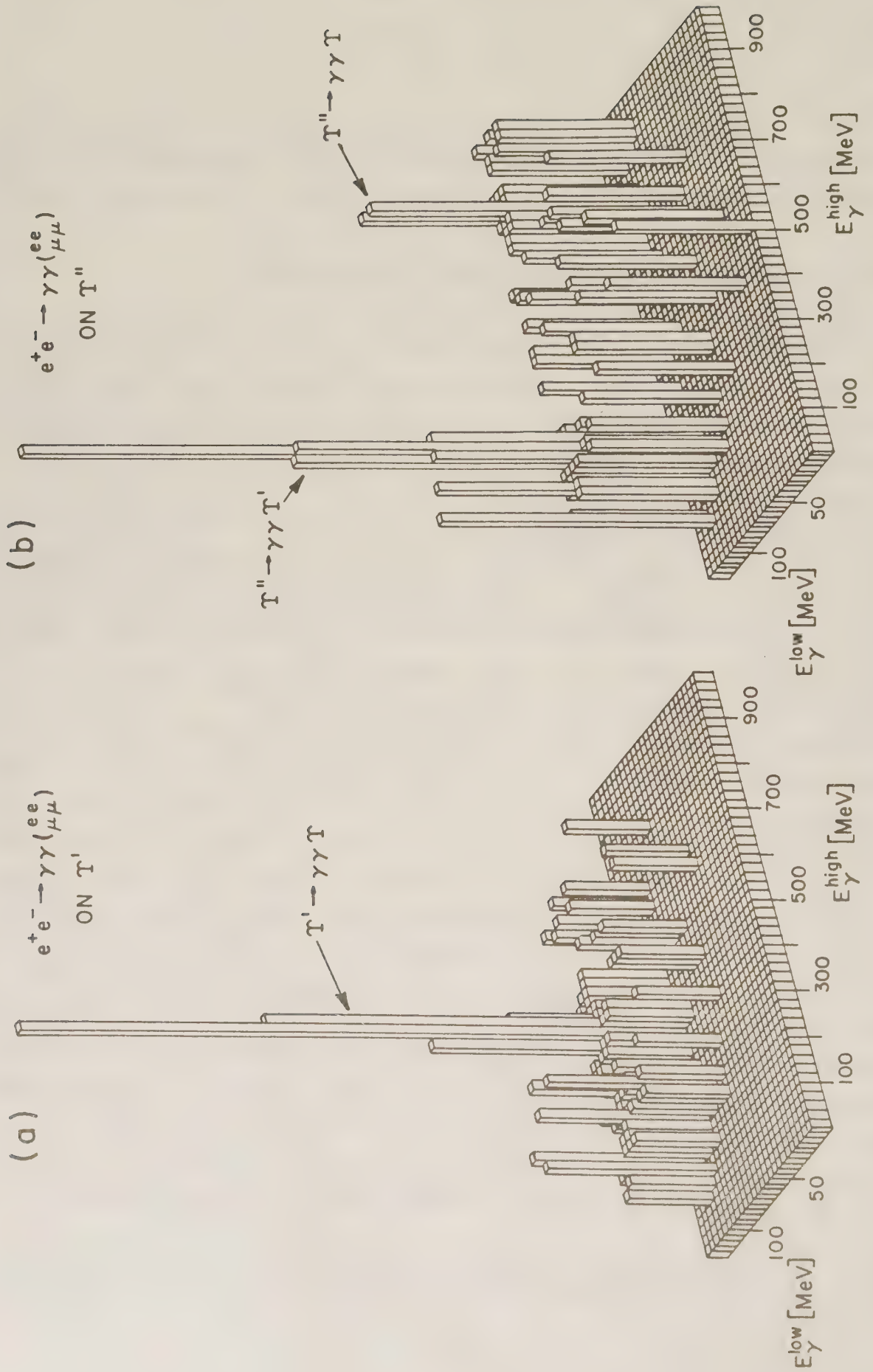


Fig. 4.28 Three dimensional $\nu\nu$ correlation plot ('Manhattan plot').

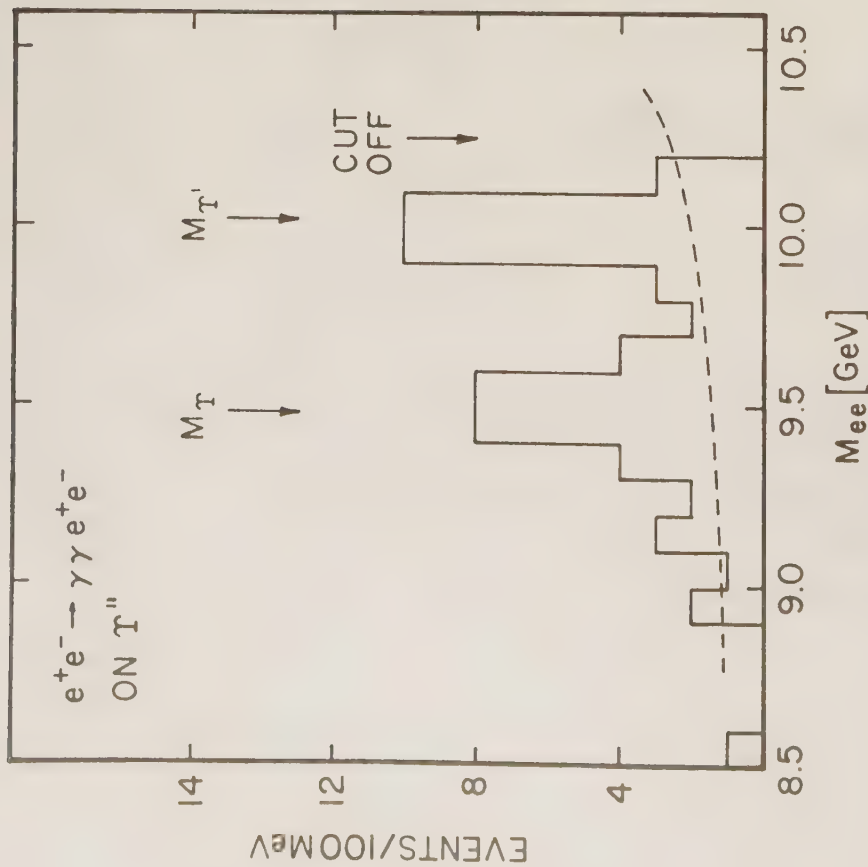


Fig. 4.30 Invariant e^+e^- mass spectrum from $T'' \rightarrow \gamma\gamma e^+e^-$ events. The dashed line indicates an estimate for the background from double Bhabha scattering.

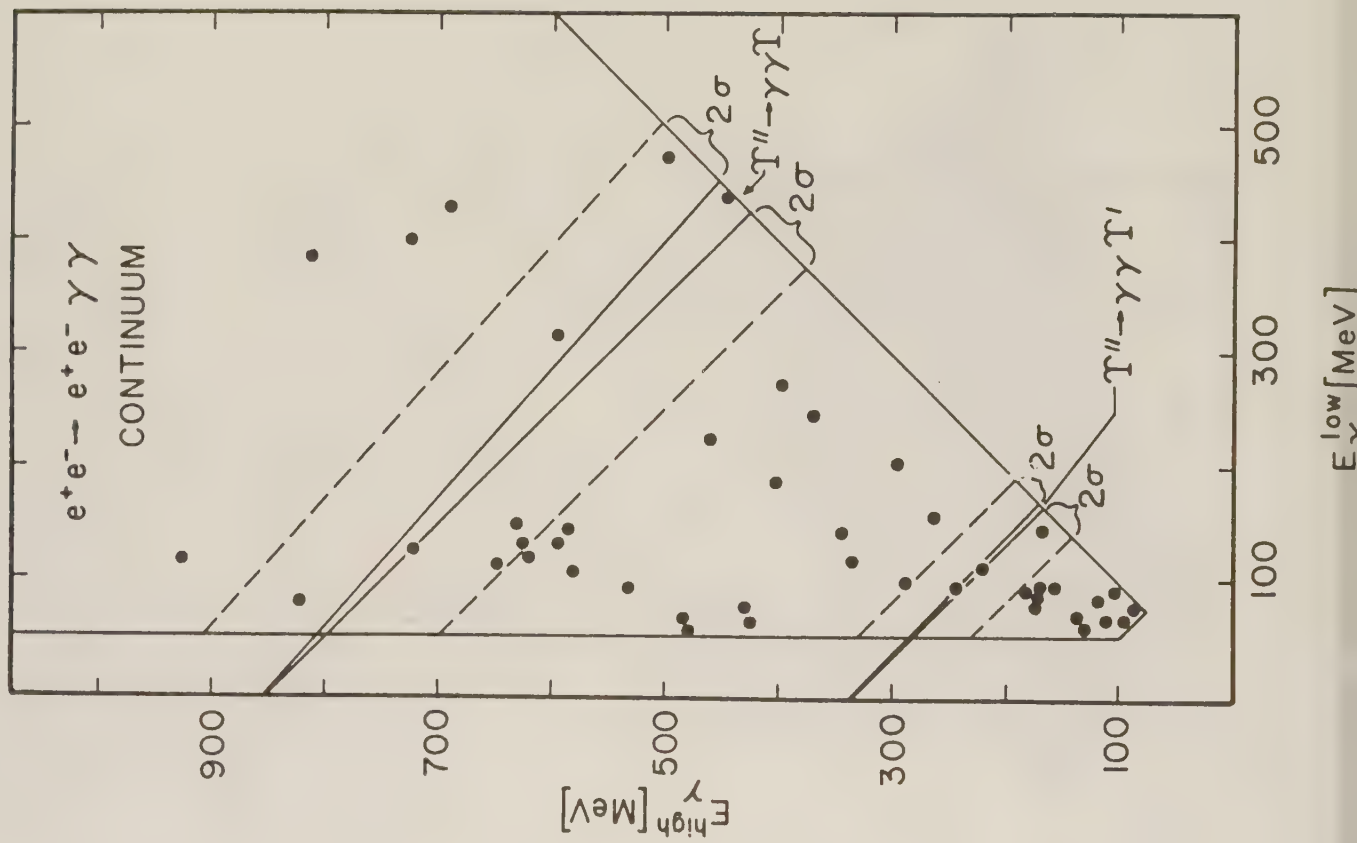


Fig. 4.31 Scatter plot of the higher versus the lower energy photon from $\gamma\gamma e^+e^-$ events in the continuum.

The dashed line indicates the background contribution from double Bremsstrahlung of Bhabha scatters. Also the invariant e^+e^- pair mass M_{ee} , shown in fig. 4.30, indicates that in fact transitions to the 2S and 1S are observed.

Due to the observation of ~ 100 MeV photons in both transitions the assignment of the λ_b' mass is unambiguous. We therefore conclude that the λ_b' states are located ~ 100 MeV below the T'' in good agreement with theoretical predictions.

IV.3.5.2 Background Studies

The background in the $\gamma\gamma\mu\mu$ and $\gamma\gamma ee$ samples results essentially from the same processes we discussed in section IV.2.5.2, however, with different individual contributions. Using again MC studies we predict 1 ± 1 background events in the entire scatter plot for the process $e^+e^- \rightarrow \tau^+\tau^- \rightarrow (\mu\nu\bar{\nu})(\rho\nu) \rightarrow \mu\pi\gamma\gamma$. Double Bremsstrahlung from initial state radiation of Bhabhas contributes at most 1 event in the $\gamma\gamma\mu\mu$ sample. From both hadronic transitions $T'' \rightarrow \pi^0\pi^0 T(T') \rightarrow \gamma\gamma\gamma\gamma\mu\mu$, where two photons remain undetected, we expect at most 1 event, since both the corresponding BR's and number of produced T'' decays are substantially smaller than for the T' data set. This is in excellent agreement with the result from the continuum scan, yielding 1 event. We therefore conclude that within the 2σ -bands the $T'' \rightarrow \gamma\gamma\mu\mu$ sample is basically background-free.

The dominant background in the $\gamma\gamma ee$ sample again results from double Bremsstrahlung of Bhabha scatters. To extract the contribution of this background source for both transitions we have reanalyzed our continuum sample (equivalent to 17.5 nb^{-1}), requiring the same selection criteria as for the T'' data and adjusting photon energies by $M_{T'}/2E_{\text{beam}}$. As shown in fig. 4.31, we observe 5 (3) events inside the 2σ -bands with E_{γ}^{low} restricted to $60 \leq E_{\gamma}^{\text{low}} \leq 140$ MeV for the transitions $T'' \rightarrow \gamma\gamma T(T')$. To increase statistics we have additionally included 3 (8) events from the same two energy bands of the $T' \rightarrow \gamma\gamma ee$ data sample. To reduce the contribution from $T' \rightarrow \pi^0\pi^0 T$, 5 events have been subtracted in the lower 2σ -bands. Scaling the integrated luminosities we obtain 2.6 ± 1.0 and 3.6 ± 1.1 background events inside the 2σ -bands restricted to $60 \leq E_{\gamma}^{\text{low}} \leq 140$ MeV for the transitions $T'' \rightarrow \gamma\gamma T$ and $T'' \rightarrow \gamma\gamma T'$, respectively. For comparison, the background in the entire 2σ -bands is 5.6 ± 1.4 and 4.3 ± 1.1 events, respectively.

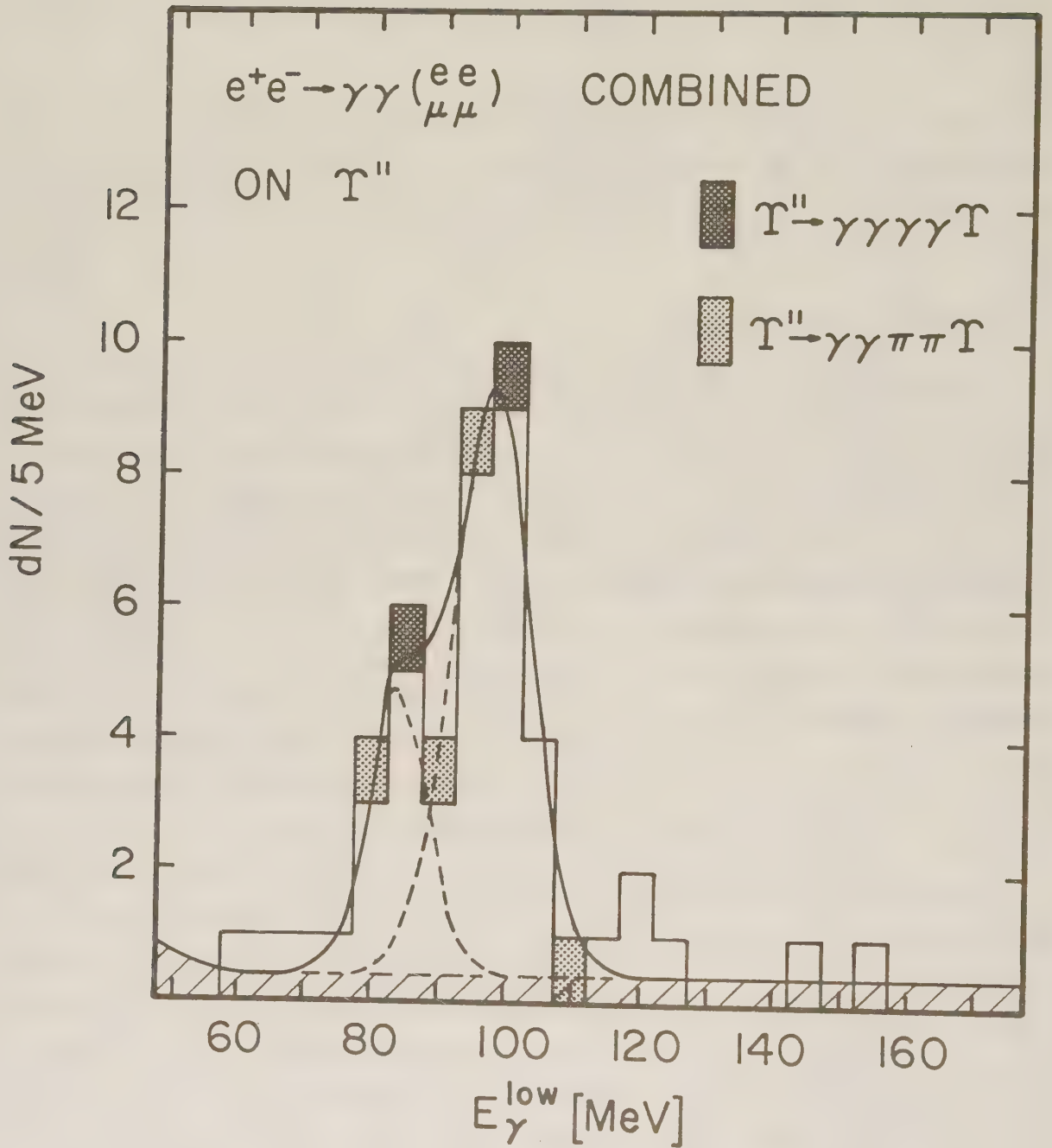


Fig. 4.32 The lower energy photon spectrum for all exclusive $\gamma\gamma\mu^+\mu^-$ or $\gamma\gamma e^+e^-$ decays inside the 2σ bands of the $\gamma\gamma$ correlation plots in figs. 4.27a and 4.27b after constraining the energy sum of both photons to the $T''-T'$ or $T''-T$ mass difference. In addition two events from $T'' \rightarrow \gamma\chi_b' \rightarrow \gamma\gamma T' \rightarrow \gamma\gamma\gamma\chi_b \rightarrow \gamma\gamma\gamma\gamma (T \rightarrow e^+e^-)$ and 4 events from $T'' \rightarrow \gamma\chi_b' \rightarrow \gamma\gamma T' \rightarrow \gamma\gamma\pi\pi (T \rightarrow e^+e^-)$ have been included. The solid line shows the fit of two gaussians with widths fixed to the observed energy resolution over a constant background of 0.4 events/bin.

The second method, where 5000 single radiative Bhabha's have been randomly combined to simulate double Bremsstrahlung yields 5.0 ± 0.8 (4.3 ± 0.5) events inside the entire 2σ -bands and 2.0 ± 0.3 (3.7 ± 0.4) events inside the 2σ -bands restricted to $60 \leq E_{\gamma}^{\text{low}} \leq 140$ MeV for the corresponding transitions, in excellent agreement with the above results. The hadronic transitions $\Upsilon'' \rightarrow \pi^0 \pi^0 \Upsilon(\Upsilon') \rightarrow \gamma \gamma \gamma e e$ with two photons undetected yields about 1 event in the entire scatter plot. Contributions from possible η transitions are again negligible.

IV.3.5.3 χ_b' Fine Structure

To search for fine splitting of the χ_b' states we have combined the data of both the $\gamma\gamma\mu\mu$ and $\gamma\gamma e e$ samples accepting again only events inside the 2σ -bands (a total of 42 events). In addition, to increase statistics, we have added 6 multiple cascade events, 2 resulting from $\Upsilon'' \rightarrow \gamma \chi_b' \rightarrow \gamma \gamma \Upsilon' \rightarrow \gamma \gamma \gamma \chi_b \rightarrow \gamma \gamma \gamma \gamma (\Upsilon \rightarrow e e, \mu\mu)$ with all four photons observed and 4 from $\Upsilon'' \rightarrow \gamma \chi_b' \rightarrow \gamma \gamma \Upsilon' \rightarrow \gamma \gamma \pi^+ \pi^- \Upsilon$ with two photons and two charged pions observed (see section IV.4). The photon energies are corrected in the manner of section IV.2.5.3, where this time the $\Upsilon'' - \Upsilon$ and $\Upsilon' - \Upsilon$ mass differences are used, reduced by the Υ -recoil, i.e. 859 MeV and 326 MeV for CESR energy scale. The remaining systematic uncertainties are ≤ 1 MeV. In addition, we gain about 17% in energy resolution, yielding 6% at 100 MeV.

Fig. 4.32 displays the resulting spectrum for E_{γ}^{low} . A large enhancement is visible (a 21σ -effect) showing a shoulder on the lower energy side. However, a single line fit, using a single gaussian curve with free height and peak position but fixed resolution of 6% over a constant background of .4 events/bin, is inconsistent with the observed spectrum. The χ^2 yields 17.3 for 7 dof, corresponding to $\leq 2\%$ CL. We therefore fit the spectrum with two gaussian curves. Peak positions and heights are again allowed to vary whereas the resolution is kept fixed. The fit yields positions at (83.3 ± 2.6) MeV and (98.0 ± 1.7) MeV with a χ^2 of 5.3 for 10 dof, corresponding to a CL $> 87\%$. The observed intensity ratio (not corrected for acceptance) is $(0.41 \pm 0.18):1$. In addition we have again allowed resolution and background to vary freely, finding that the line positions are very stable. Finally, we also tried to fit the spectrum to three gaussians, yielding an additional line at (118 ± 5.6) MeV without changing the positions of the two other lines considerably ($\chi^2 = 4.1$ for 12 dof). However, the third peak only shows a 3.5σ effect. Furthermore, some of these events might belong to the tail of the line at 99 MeV. Therefore we also regard a

Table 4.9 Fit parameters for different fit functions to E_{γ}^{low} for λ_b production

fit function	data sample	bckgrnd [events]	Epeak [MeV]	σ_{rms} [MeV]	Irel	χ^2/dof	CL [%]
2 gaussians	A	.4	83.3 $\pm$ 2.6 98.0 $\pm$ 1.7	5.0 5.9	.41 $\pm$.18 1	5.3/10	>87
2 gaussians	B	.4	83.1 $\pm$ 2.9 98.0 $\pm$ 1.3	5.0 5.9	.36 $\pm$.18 1	5.3/10	>87
2 gaussians	A'	.4	83.2 $\pm$ 3.1 99.7 $\pm$ 1.9	5.0 5.9	.53 $\pm$.23 1	6.1/10	>80
2 gaussians+ conc. bckgrnd	A ^{+))}	1.21 $\pm$.38	84.0 $\pm$ 1.9 98.1 $\pm$ 1.2	3.6 $\pm$ 0.7 4.2 $\pm$ 0.8	.42 $\pm$.20 1	0.3/3	>95
3 gaussians	A	.4	83.1 $\pm$ 2.8 97.7 $\pm$ 1.8 118.8 $\pm$ 5.6	5.0 5.9 7.1	.41 $\pm$.18 1 .13 $\pm$.09	4.1/12	>98
3 gaussians	B	.4	83.1 $\pm$ 2.9 97.8 $\pm$ 1.8 119.2 $\pm$ 5.3	5.0 5.9 7.1	.35 $\pm$.18 1 .14 $\pm$.10	5.5/12	>93
3 gaussians+ cons. bckgrnd	A ^{+))}	.71 $\pm$.45	83.8 $\pm$ 1.9 98.1 $\pm$ 1.2 118.8 $\pm$ 5.1	3.7 $\pm$ 0.7 4.3 $\pm$ 0.8 5.2 $\pm$ 1.0	.45 $\pm$.20 1 .10 $\pm$.27	1.0/5	>95
1 gaussian	A ^{+))}	.4	93.3 $\pm$ 0.9	5.9		17.3/7	<2
1 gaussian	B ^{+))}	.4	94.8 $\pm$ 1.2	5.9		14.1/8	<9
1 gaussian	A', ^{+))}	.4	95.5 $\pm$ 0.9	5.9		25.2/9	<1

A: entire data sample consisting of all $\gamma\gamma\mu\mu$, all $\gamma\gamma ee$ plus 2 the $\gamma\gamma\gamma ee$ and the 3 $\gamma\gamma\pi\pi ee$ events

B: $\gamma\gamma ee$ and $\gamma\gamma\mu\mu$ events only

A': sample A with binning shifted by 2.5 MeV

^{+))} Background (constant) and resolution are kept as free parameters. For all other fits background and resolution are fixed to the measured values.

two line fit to be more realistic. But contrary to the peaks in the E_{γ}^{low} -spectrum of the $\mathbf{T}' \rightarrow \gamma\gamma\mathbf{T}$ data sample the two lines in this spectrum cannot be fully resolved because of a smaller fine splitting and a poorer energy resolution. The results for different fits are listed in detail in table 4.9.

In order to account for the absolute mass scale we finally have to correct all energies upward by 1/2% yielding (83.8 ± 2.6) MeV and (98.6 ± 1.7) MeV, respectively. As discussed before, systematic uncertainties are less than 1 MeV. The positions are also in excellent agreement with the two lower line positions observed in the corresponding background subtracted inclusive photon spectrum (see next section). The two lines observed at 85 MeV and 100 MeV are attributed to the transitions via the $J=2$ and $J=1$ 2^3P_J state, respectively.⁺) The suppression of cascade decays via the $J=0$ transition is explained by the same arguments given in Section IV.2.5.3.

IV.3.6 Results from the Inclusive Photon Analysis

The search for χ_b' production in the inclusive photon spectrum is performed by analyzing 88,000 hadronic events collected at the $\mathbf{T}'$ peak in the same running period, of which 48,000 events are resonance decays [Hn 83, Kl 83]. The photon selection criteria are essentially the same as for the analysis of the $\mathbf{T}'$ data sample. The photon energies are determined by adjusting the raw energies by an average correction factor of 1.15 neglecting all angular effects. Again we have accepted all energies between 22 MeV and 2200 MeV. To determine the resolution and recovery efficiency for photons in the 100 MeV range, MC generated photon showers were randomly superimposed on hadronic events, which in turn were processed through the same photon finding code. After adjusting photon energies by 1.15 the single line spectrum plotted in fig. 4.34b was obtained. The resolution is $\sim 8\%$ at 100 MeV. The validity of this procedure has been checked by reconstructing π^0 's from hadronic events (see IV.3.3). Furthermore, MC generated π^0 's added to real events have also been analyzed, yielding an excellent agreement for the mass spectra of real π^0 's with the ones from the MC simulation. The systematic uncertainty in the absolute energy scale is estimated to be $< 3\%$. The energy dependence of the resolution can be approximated by $\sigma_E/E \sim 4.5\%/\sqrt{E}$ (GeV). For further details see [Hn 83].

⁺) Again due to the even smaller statistics in the data samples at the $\mathbf{T}'$, the angular distributions cannot be measured experimentally.

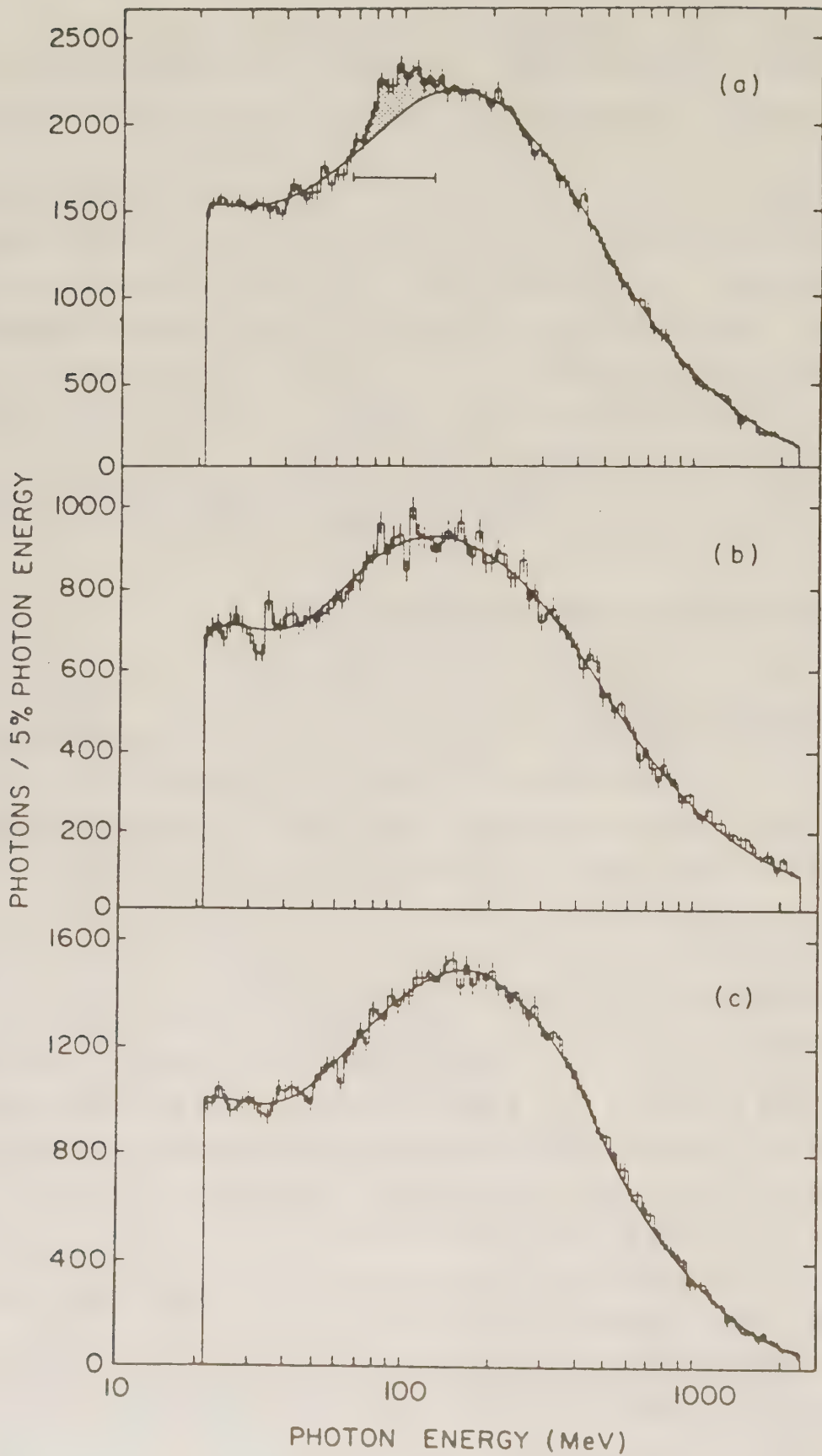


Fig. 4.33 The inclusive photon spectrum observed in hadronic decays a) of the T'' , b) of the continuum, and c) of the T . The solid curves are fits to a polynomial.

Fig. 4.33a shows the inclusive photon spectrum obtained at the T'' peak, plotted in 5% energy bins, together with the spectra from continuum and T data (figs. 4.33b,c). The photon spectrum in fig. 4.33a shows a large excess around 100 MeV above a very large background from photons of π^0 decays and 'fake clusters' at low energies, whereas no excess is observed in the spectra from continuum and T data. Contributions from the hadronic transitions $T'' \rightarrow \pi^0 \pi^0 T(T')$ are rather small. Due to the small photon finding efficiency a π^0 subtraction again does not reduce the background substantially. To model the background distribution in fig. 4.33a we again use the methods described in Section IV.2.6. First, we linearly combine the observed spectra for continuum and T data, and scale to the corresponding numbers of hadronic events. The coefficients (60% T and 40% continuum) are obtained from the thrust analysis, reproducing the thrust distribution for the T'' data sample by a linear combination of thrust distributions for T and continuum data (see fig. 4.16b). This procedure is again independent of the observed photon spectrum shown in fig. 4.33a. Second, the inclusive photon spectrum from the T'' is fitted to a 9th order polynomial excluding the excess region at 100 MeV. The fit gives a χ^2 of 77 for 73 dof. For comparison a fit of the entire spectrum to a 9th order polynomial yields a χ^2 of 148 for 86 dof (i.e. a CL of $\sim 6 \times 10^{-5}$). Both methods give consistent results which are indistinguishable to the eye. The background curves shown in figs. 4.33 result from the polynomial fits. The natural explanation for the excess around 100 MeV is that photons from the transition $T'' \rightarrow \gamma \chi_b'$ are observed.

To extract the excess photons in fig. 4.33a we subtract the background curve from the observed photon spectrum. The resulting spectrum shown in fig. 4.34a contains 2240 excess photons between 60 to 130 MeV (a 10σ signal). Fitting three gaussians to the spectrum with arbitrary intensity and position but with widths determined from the resolution in fig. 4.34b yields a χ^2 of 16 for 14 dof, i.e. a CL of 32%. Peak positions of $(84.2 \pm 0.3 \pm 2)$ MeV, $(101.4 \pm 0.3 \pm 3)$ MeV, and $(122.1 \pm 0.7 \pm 5)$ MeV have been obtained. The first errors quoted are the diagonal elements of the error matrix and do not take into account the strong correlation between intensity and peak position of the lines. The additional systematic uncertainty per position is given by the second error. A fit with only two gaussians yields positions at (86.3 ± 1.2) MeV and (105.7 ± 1.5) MeV with a χ^2 of 23.7 for 16 dof, i.e. a CL of $\sim 9\%$. A single line fit gives a CL of $< 10^{-5}$. The line positions are again rather stable with a shift of the background.

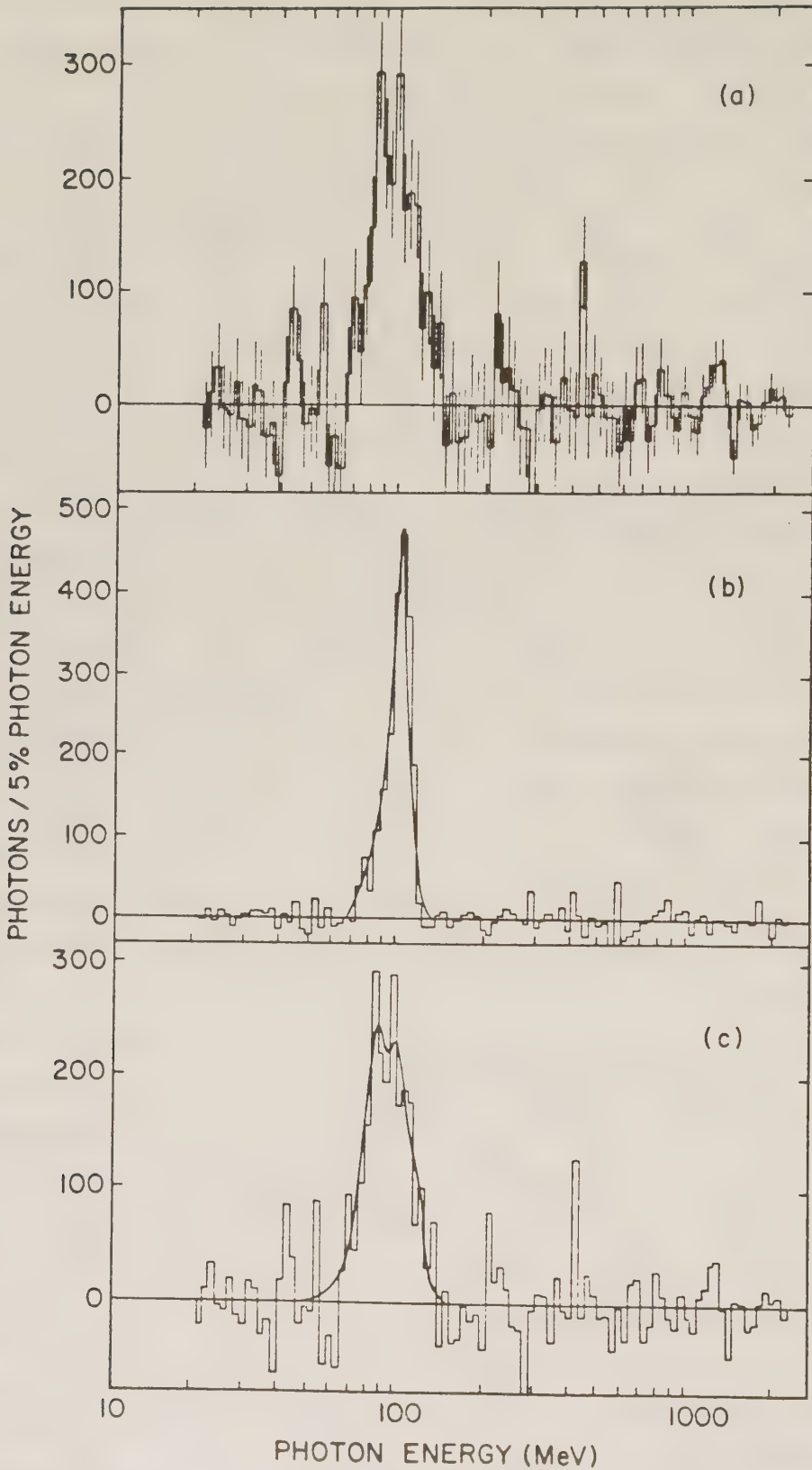


Fig. 4.34 a) The background subtracted inclusive photon spectrum including error bars.
 b) Background subtracted energy spectrum for 100 MeV Monte Carlo generated photons which have been superimposed on real hadronic events. The solid line represents a fit of two Gaussians of widths 6.7% and 17.5% of the peak position, where the wider gaussian is displaced down by 10% and contributes 35% to the total area.
 c) A fit of three gaussians with widths fixed to the observed resolution.

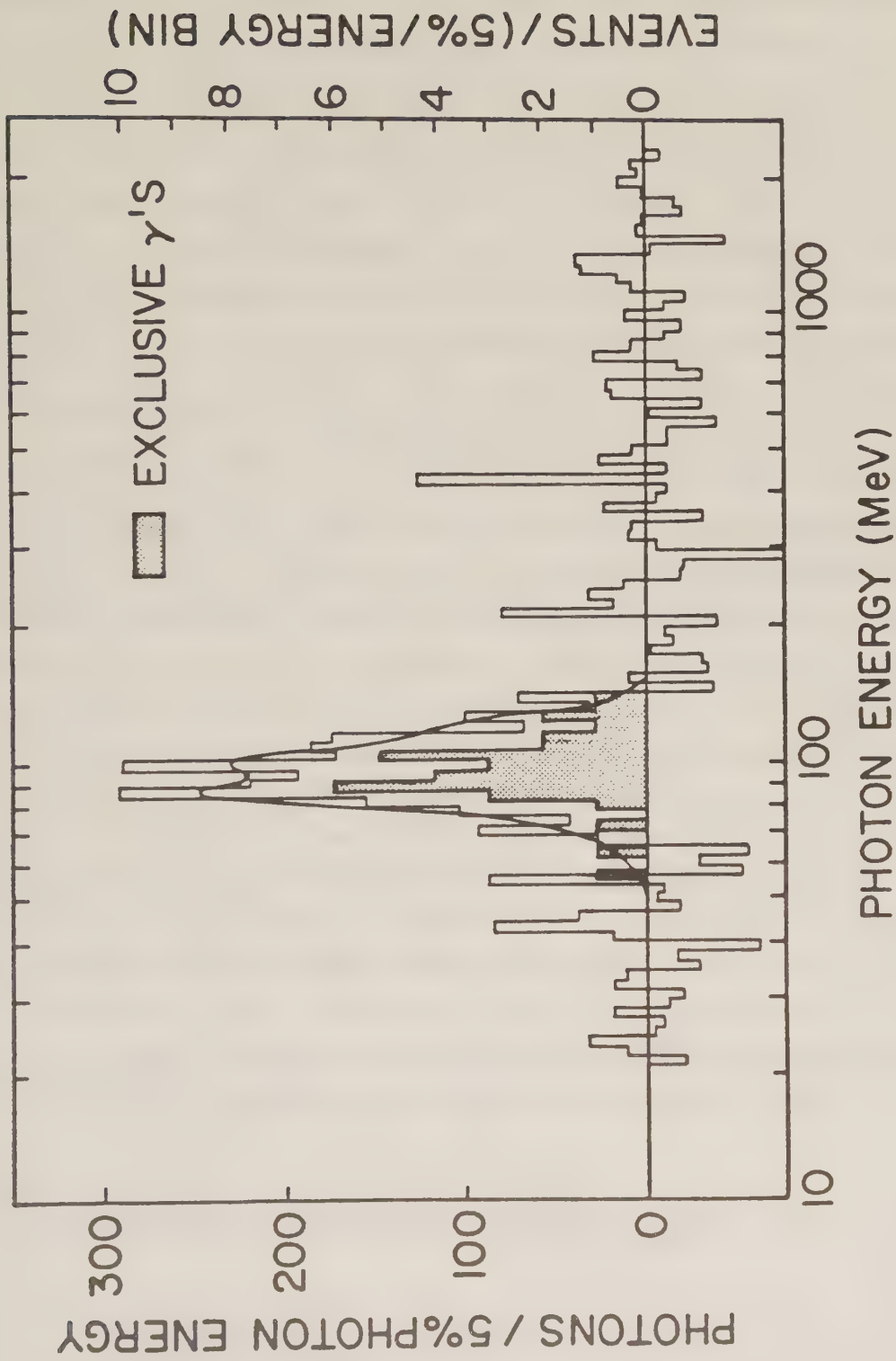


Fig. 4.35 Comparison of the lower energy photon spectrum of the exclusive T'' decays shown in fig. 4.32 with the background subtracted inclusive photon spectrum of fig. 4.34a.

Photons from the mirror lines $\lambda_b' \rightarrow \gamma T'$ or $\lambda_b' \rightarrow \gamma T$ are expected around 230 MeV and 760 MeV, respectively. In the background subtracted inclusive photon spectrum a small enhancement of $\sim 140 \pm 100$ events around 230 MeV (only a 1.5σ effect) is visible, but no obvious signal is found around 760 MeV. Summing up eight energy bins between 620 and 900 MeV yields 60 ± 140 events. In comparison the background of the corresponding region is 7000 events. On the other hand, from the measured BR's for the exclusive cascade transitions we expect 330 ± 140 and 200 ± 100 excess events, respectively. However, the background estimate in the inclusive spectrum is slightly pessimistic, since the 230 MeV and 760 MeV regions have not been excluded from the fit. In addition the statistical error in the 760 MeV range is $\sim \pm 30$ events per bin, which is of the same order as the expected excess. Therefore we conclude that the observed spectrum is still consistent with the expected excess number of photons for the mirror lines.

For comparison fig. 4.35 shows both the background subtracted inclusive photon spectrum and the low energy spectrum from the exclusive cascade events. An excellent agreement for the two lower lines is observed.

IV.3.7 λ_b' Masses

The λ_b' masses are now determined by subtracting E_γ^{low} from $M_{T'}$, $= 10,355.5$ MeV and correcting by ~ 0.5 MeV for recoil effects. Table 4.10 summarizes the individual masses obtained both from the inclusive background subtracted photon spectrum and the lower energy photon spectrum of the exclusive photon cascade events. An excellent agreement for the $J=2$ and $J=1$ 2^3P_J states is observed. The errors quoted contain both statistical and systematic uncertainties. The observed level spacings are $M(2^3P_2 - 2^3P_1) = (15.4 \pm 2.3)$ MeV and $M(2^3P_1 - 2^3P_0) = (22.9 \pm 5.2)$ MeV. For the weighted λ_b' center-of-gravity we determine $M(2^3P_{\text{cog}}) = (10262 \pm 1.5)$ MeV.

Table 4.10 λ_b' masses obtained from the inclusive and exclusive photon analyses.

	M(inc) [MeV]	M(exc) [MeV]	$\bar{M}$ [MeV]
2^3P_0	10233 ± 5	-----	10233 ± 5
2^3P_1	10254 ± 3	10256 ± 2	10256 ± 2
2^3P_2	10271 ± 2	10271 ± 3	10271 ± 2
1^3P_{cog}	10261 ± 2	-----	10262 ± 1.5

IV.3.8 Branching Ratios

The product branching ratios for the photon cascades from the $\mathbf{T}'$ have been determined by a procedure similar to that discussed in IV.2.8. The $\mathbf{T}'$ data sample used for the analysis of the exclusive reactions contains 90,000 hadronic events that passed the hadron selection criteria. The portion of continuum events underlying the resonance is 41,700 events,+) thus leaving 48,300 observed resonance decays. To obtain the total number of resonance events produced we have to correct for the hadron detection efficiency of $\varepsilon_{\text{had}}(\mathbf{T}')=0.82\pm0.03$ and account for all decay modes of the $\mathbf{T}'$ which are not contained in the hadronic sample. We estimate this latter correction to be $5\pm3\%$,++) yielding $62,000\pm4,000$ produced resonance events.

The total number of $\gamma\gamma\mu\mu$ and γee events observed in the lower energy photon spectrum in the range $69\leq E_{\gamma}^{\text{low}}\leq 118$ MeV is $N_{\text{obs}}=16$ (16) events for $\mathbf{T}'\rightarrow\gamma\gamma\mathbf{T}'(\mathbf{T})$, excluding three events with a projected dip $\delta>42.5^\circ$ (outside the fiducial volume) for the e^+e^- pair. The corresponding background is $N_{\text{bg}}=2.2$ (1.6) events. The relative fractions between the two lines have been determined from the spectrum in fig. 4.32 to be $f_2=.28\pm.1$ ($.25\pm.1$) and $f_1=.72\pm.1$ ($.75\pm.1$) for $\mathbf{T}'\rightarrow\gamma\gamma\mathbf{T}'(\mathbf{T})$. Using the detection efficiencies listed in table 4.8 and the values of $B_{\mu\mu}$ in table 2.4 one obtains from eq. (4.14) the product branching ratios for $\mathbf{T}'\rightarrow\gamma\gamma\mathbf{T}'$ and $\mathbf{T}'\rightarrow\gamma\gamma\mathbf{T}$ summed over the intermediate $J=1$ and $J=2$ χ_b' states:

$$\sum_{J=1}^2 \text{BR}(\mathbf{T}'\rightarrow\gamma 2^3P_J) \times \text{BR}(2^3P_J\rightarrow\gamma\mathbf{T}')=(5.0\pm2.1)\% \quad (4.21)$$

$$\sum_{J=1}^2 \text{BR}(\mathbf{T}'\rightarrow\gamma 2^3P_J) \times \text{BR}(2^3P_J\rightarrow\gamma\mathbf{T})=(3.6\pm1.1)\% \quad (4.22)$$

From the above quoted fractions one determines the product BR's for the transitions via the individual $J=1$ and $J=2$ χ_b' states:

$$\text{BR}(\mathbf{T}'\rightarrow\gamma 2^3P_2) \times \text{BR}(2^3P_2\rightarrow\gamma\mathbf{T}')=(1.5\pm0.9)\% \quad (4.23a)$$

$$\text{BR}(\mathbf{T}'\rightarrow\gamma 2^3P_1) \times \text{BR}(2^3P_1\rightarrow\gamma\mathbf{T}')=(3.5\pm1.8)\% \quad (4.23b)$$

+) The continuum contribution has been determined from a continuum cross-section of $\sigma_{\text{con}}(\mathbf{T}')=(2.67\pm0.3)$ nb and the luminosity of 15.6 pb^{-1} for the $\mathbf{T}'$ data sample.

++) We have used $B_{\mu\mu}(\mathbf{T}')=(1.5\pm.2)\%$ as derived in appendix A, the CUSB measurement $\text{BR}(\mathbf{T}'\rightarrow\pi^+\pi^-\mathbf{T}')=(3.0\pm1.9)\%$, the average of CLEO and CUSB for $\text{BR}(\mathbf{T}'\rightarrow\pi^+\pi^-\mathbf{T})=(4.8\pm0.8)\%$, the measured values for $B_{\mu\mu}(\mathbf{T})$, $B_{\mu\mu}(\mathbf{T}')$ in table 2.4 and the fractions quoted in IV.2.8.

$$\text{BR}(\mathbf{T}'' \rightarrow \gamma 2^3\text{P}_2) \times \text{BR}(2^3\text{P}_2 \rightarrow \gamma \mathbf{T}) = (1.0 \pm 0.5)\% \quad (4.24a)$$

$$\text{BR}(\mathbf{T}'' \rightarrow \gamma 2^3\text{P}_1) \times \text{BR}(2^3\text{P}_1 \rightarrow \gamma \mathbf{T}) = (2.6 \pm 1.0)\% \quad (4.24b)$$

For the product BR's via the $J=0$ states we deduce upper limits from the 3 (0) events observed in the energy range $118 \leq E_\gamma^{\text{low}} \leq 140$ MeV. Considering a background expectation of 1.0 event for $\mathbf{T}'' \rightarrow \gamma \gamma \mathbf{T}'$ and using the event detection efficiencies from table 4.8 we get:

$$\text{BR}(\mathbf{T}'' \rightarrow \gamma 2^3\text{P}_0) \times \text{BR}(2^3\text{P}_0 \rightarrow \gamma \mathbf{T}') < 2.2\% \quad (90\% \text{ CL}) \quad (4.23c)$$

$$\text{BR}(\mathbf{T}'' \rightarrow \gamma 2^3\text{P}_0) \times \text{BR}(2^3\text{P}_0 \rightarrow \gamma \mathbf{T}) < 0.7\% \quad (90\% \text{ CL}) \quad (4.24c)$$

For the transition $\mathbf{T}'' \rightarrow \gamma \lambda_b \rightarrow \gamma \gamma \mathbf{T}$ we determine an upper limit from the 4 events observed in the correlation plots of both $\gamma \gamma \mu \mu$ and $\gamma \gamma e e$ samples inside the 2σ -bands and the energy range $370 \leq E_\gamma^{\text{low}} \leq 500$ MeV. Considering a background of 1 event and an average detection efficiency of .24 we estimate for the sum of product BR's via intermediate λ_b production:

$$\sum_{J=1}^2 \text{BR}(\mathbf{T}'' \rightarrow \gamma 1^3\text{P}_J) \times \text{BR}(1^3\text{P}_J \rightarrow \gamma \mathbf{T}) < 1.6\% \quad (90\% \text{ CL}) \quad (4.25)$$

From eq. (4.25) and the results in IV.2.8 we can determine an upper limit for $\text{BR}(\mathbf{T}'' \rightarrow \gamma \lambda_b)$. Since the individual branching ratios are proportional to $(2J+1)k_\gamma^3$ one evaluates from the measured $3^3\text{S}_1 - 1^3\text{P}_J$ mass differences intensity ratios of 1.46:1:0.38 for transitions via the $J=2$, $J=1$, and $J=0$ states. Assuming that $\text{BR}(\mathbf{T}'' \rightarrow \gamma 1^3\text{P}_0) \times \text{BR}(1^3\text{P}_0 \rightarrow \gamma \mathbf{T})$ is negligible we estimate:

$$\sum_{J=1}^2 \text{BR}(\mathbf{T}'' \rightarrow \gamma 1^3\text{P}_J) < 5.2\% \quad (90\% \text{ CL}) \quad (4.26)$$

From the 2240 excess photons, a photon recovery efficiency of 13% and the number of observed $\mathbf{T}''$ resonance decays corrected for all non-hadronic decay modes we determine for the E1 transition $\mathbf{T}'' \rightarrow \gamma \lambda_b$ a total BR of:

$$\sum_{J=0}^2 \text{BR}(\mathbf{T}'' \rightarrow \gamma 2^3\text{P}_J) = (35.9 \pm 3 \pm 4)\% \quad (4.27)$$

For the individual transitions we derive the BR's:

$$\text{BR}(\mathbf{T}'' \rightarrow \gamma 2^3\text{P}_2) = (12.7 \pm 4.1)\% \quad (4.28a)$$

$$\text{BR}(\mathbf{T}'' \rightarrow \gamma 2^3\text{P}_1) = (15.6 \pm 4.2)\% \quad (4.28b)$$

$$\text{BR}(\mathbf{T}'' \rightarrow \gamma 2^3\text{P}_0) = (7.6 \pm 3.5)\% \quad (4.28c)$$

where the systematic errors have been omitted.

Dividing the product BR's in eqs. (4.23a,b) and (4.24a,b) by eqs. (4.28a,b), one obtains the BR's for E1 transitions from the λ_b' states to the lower lying 3S_1 states:

$$BR(2^3P_2 \rightarrow \gamma T') = (12 \pm 8)\% \quad (4.29a)$$

$$BR(2^3P_1 \rightarrow \gamma T') = (22 \pm 13)\% \quad (4.29b)$$

$$BR(2^3P_2 \rightarrow \gamma T) = (8 \pm 5)\% \quad (4.30a)$$

$$BR(2^3P_1 \rightarrow \gamma T) = (17 \pm 8)\% \quad (4.30b)$$

Finally, for the E1 transitions from the 2^3P_0 state we can derive an upper limit:

$$BR(2^3P_0 \rightarrow \gamma T') < 29\% \quad (90\% \text{ CL}) \quad (4.29c)$$

$$BR(2^3P_0 \rightarrow \gamma T) < 9\% \quad (90\% \text{ CL}) \quad (4.30c)$$

IV.4 Multiple Cascade Transitions

In addition to the analysis of the $\gamma\gamma$ cascades we have also performed a scan of the T'' sample to search for exclusive events from the following multiple cascade transitions:

$$A. \quad T'' \rightarrow \gamma \lambda_b' \rightarrow \gamma \gamma T' \rightarrow \gamma \gamma \gamma \lambda_b \rightarrow \gamma \gamma \gamma \gamma (T \rightarrow e^+e^- \text{ or } \mu^+\mu^-)$$

$$B. \quad T'' \rightarrow \gamma \lambda_b' \rightarrow \gamma \gamma T' \rightarrow \gamma \gamma \pi^+\pi^- (T \rightarrow e^+e^- \text{ or } \mu^+\mu^-)$$

$$C. \quad T'' \rightarrow \pi^+\pi^- T' \rightarrow \pi^+\pi^- \gamma \lambda_b \rightarrow \pi^+\pi^- \gamma \gamma (T \rightarrow e^+e^- \text{ or } \mu^+\mu^-)$$

The number of expected events is rather small, since several small BR are multiplied and the detection efficiency is reduced due to the higher particle multiplicity. We therefore keep the selection criteria as loose as possible. This is justified because the background for these multiple transitions is expected to be very small.

Candidates for reaction A were selected from the $\pi^0\pi^0(ee \text{ or } \mu\mu)$ samples. We required to observe 4 photons reasonably separated from each other in addition to the lepton pair, where at least 3 out of the 4 γ 's had to be located in the CD. No explicit fiducial cuts have been applied. In order to eliminate events from the hadronic cascade transition $T'' \rightarrow \pi^0\pi^0 T$ we required the two energy sums for one (out of 3 possible) combination of photon pairs to agree with both the $T'' - T'$ and $T' - T$ mass differences corrected for recoil and Doppler broadening. In addition at least one of the two invariant masses $M_{\gamma\gamma}$ for each of the three possible combinations had to deviate significantly (by $>5\sigma$) from the π^0 mass. The detection

efficiency for events from reaction A is estimated to be of the order of ~15% summed over all event classes. Using the measured branching fractions for $\Upsilon'' \rightarrow \gamma\gamma\Upsilon'$, $\Upsilon' \rightarrow \gamma\gamma\Upsilon$ and $B_{\mu\mu}$ we expect about $.3 \pm .16$ candidates in the Υ'' data sample. However, two events (both $ee\gamma\gamma\gamma\gamma$) have been found in the scan. Since photons from the hadronic $\pi^0\pi^0$ transition are the only background source, which have been eliminated by the invariant mass and energy sum cuts, we consider this event sample to be background-free. The relevant properties of both events are summarized in table 4.11.

For events from reactions B and C we required that besides the lepton pair at least one pion and both photons reasonably separated from the other particles have been observed. In addition at least one photon had to be in the CD. Again no explicit fiducial cuts were applied. The energy sum of both photons had to agree within $\pm 2\sigma$ with either the $\Upsilon'' - \Upsilon'$ or $\Upsilon' - \Upsilon$ mass difference corrected for recoil and Doppler broadening. For the transition $\Upsilon'' \rightarrow \pi^+\pi^-\Upsilon'$ only 52 MeV kinetic energy for both pions is available. Therefore these low energy pions are already absorbed within a few cm of NaI, a characteristic used in the event selection. From the study of the hadronic transition $\Upsilon'' \rightarrow \pi\pi\Upsilon'$ we know that the finding efficiency for low energy pions in the CD is about 70% of the efficiency for higher energy pions from $\Upsilon'' \rightarrow \pi\pi\Upsilon'$ [Ms 82]. This leads to event detection efficiencies of ~20% for reaction B and ~10% for reaction C, again summed over all event classes. Using the measured BR's for the individual transitions we expect 3.4 ± 1.6 and 0.17 ± 0.13 events, respectively. In the scan we have found 4 candidates, again only $\gamma\gamma\pi\pi ee$ events, for reaction B and none for reaction C. All four events are consistent with χ_b' production. Possible sources for background are due to the three reactions: $\Upsilon'' \rightarrow \pi^0\pi^0\Upsilon' \rightarrow \pi^0\pi^0\pi^+\pi^-\Upsilon' \rightarrow \pi^0\pi^0\pi^+\pi^-(e^+e^- \text{ or } \mu^+\mu^-)$ where two photons remain unobserved, $\Upsilon'' \rightarrow \gamma\chi_b' \rightarrow \gamma\gamma 1^3D_J \rightarrow \gamma\gamma\pi^+\pi^-(\Upsilon \rightarrow e^+e^- \text{ or } \mu^+\mu^-)$ and $\Upsilon'' \rightarrow \eta\Upsilon \rightarrow \eta(e^+e^- \text{ or } \mu^+\mu^-)$ with $\eta \rightarrow \pi^+\pi^-\pi^0$. From the first background source one expects ~0.4 events. For the second source we estimate about one event by using the predicted BR's of .5%, 4%, 2% for $2^3P_J \rightarrow \gamma 1^3D_J$, with $J=0,1,2$ (summed over all appropriate spin values J' of the 1^3D_J states) [Ei 80] and ~30% for $1^3D_J \rightarrow \pi^+\pi^-\Upsilon$ [KY 81]. The last background source is negligible, since from the scaling law $\Gamma(\Upsilon'' \rightarrow \pi\pi\Upsilon')/\Gamma(\Upsilon \rightarrow \eta\Upsilon) = 19 \cdot (m_b/m_c)^2 \simeq 150$ [KY 81] and the measured rate $\Gamma_{\pi\pi} = 1.9$ keV for $\Upsilon'' \rightarrow \pi\pi\Upsilon'$ one obtains a rate $\Gamma_{\eta} = 0.013$ keV and in turn a BR of $\simeq 0.05\%$ for $\Upsilon'' \rightarrow \eta\Upsilon$. Using a detection efficiency of 20% one therefore expects only ~.04 events. However, the photon energies for events of these background sources do not cluster around (100,230) MeV.

Since we require the energy sum of both photons to be within $\pm 2\sigma$ of the $T'^{-}T'$ mass difference the event sample for the multiple photon-hadron cascades can also be considered as background free. The relevant parameters of the four events are summarized in table 4.11.

Table 4.11 Summary of the essential properties of double cascade events.

event type	particle location	E_{γ} observed [MeV]	sum energies [MeV]	invariant mass [MeV]	E_{γ}^{low} constraint [MeV]
$\gamma\gamma\gamma\gamma ee$	ee in CD 3 γ in CD 1 γ in EC	86.3 $\pm$ 5.2 241.3 $\pm$ 14.9 121.6 $\pm$ 7.4 444.8 $\pm$ 72	327.6 $\pm$ 15.8 566.4 $\pm$ 72.4	275 $\pm$ 12 290 $\pm$ 24 236 $\pm$ 11 331 $\pm$ 29 482 $\pm$ 42 135 $\pm$ 6	86.4 120.2
$\gamma\gamma\gamma\gamma ee$	ee in EC 3 γ in CD 1 γ in EC	98.9 $\pm$ 6.0 240.2 $\pm$ 48 114.1 $\pm$ 8.0 470.8 $\pm$ 33	339.1 $\pm$ 48.4 584.9 $\pm$ 34	242 $\pm$ 26 228 $\pm$ 12 198 $\pm$ 10 523 $\pm$ 56 410 $\pm$ 19 260 $\pm$ 28	97.5 106.5
$\gamma\gamma\pi^+\pi^-ee$	ee in CD γ_{low} in CD γ_{high} in EC $\pi\pi$ in CD	75.3 $\pm$ 15 242.3 $\pm$ 19.3	317.6 $\pm$ 24.4	245 $\pm$ 27	79.8
$\gamma\gamma\pi^+\pi^-ee$	ee in CD γ_{low} in CD γ_{high} in EC one π in CD, other π lost	90.0 $\pm$ 6.3 239.4 $\pm$ 65	329.4 $\pm$ 65.3	170 $\pm$ 24	89.7
$\gamma\gamma\pi^+\pi^-ee$	ee in EC γ_{low} in CD γ_{high} in EC $\pi\pi$ in CD	93.5 $\pm$ 6.6 228.0 $\pm$ 45.6	321.5 $\pm$ 46.1	240 $\pm$ 26	94.2
$\gamma\gamma\pi^+\pi^-ee$	ee in CD γ_{low} in CD γ_{high} in CD π in CD, other π lost	96.8 $\pm$ 12 207.1 $\pm$ 16.1	303.9 $\pm$ 20.1	219 $\pm$ 17	107.8

V DISCUSSION AND OUTLOOK

V.1 Comparison of Different Experimental Results on χ_b Production

The measurements presented in this thesis on both χ_b and χ_b' production in the exclusive as well as inclusive channels of radiative T' and T'' decays have been the first experimental evidence for 1^3P and 2^3P states in the $b\bar{b}$ system. While our measurements on the χ_b' states are still the only experimental data, our results on the χ_b states have been recently confirmed by other experiments: by CLEO at CESR as well as ARGUS and Crystal Ball (CB) both operating at DORIS II.

The methods used for photon identification differ in these experiments according to the different detector configurations:

- i) The CB, a nonmagnetic spherical NaI calorimeter [Or 82], measures photons as electromagnetic showers in the NaI calorimeter, but with a better resolution of $2.4\%/\sqrt{E}(\text{GeV})$ and a larger photon finding efficiency than the CUSB detector.
- ii) The magnetic detectors ARGUS [Al 83] and CLEO [An 83] are used as pair spectrometers to measure electron energies from converted photons. While the energy resolution is excellent (e.g. $\sigma_E/E=1\%$ at $E=130$ MeV for ARGUS), the photon finding efficiency is about one order of magnitude lower than for calorimeters.

Since only the CUSB and CLEO results have been published so far [Hn 82, Hs 84, Kl 83, Pa 83], we will use for comparison the ARGUS and CB data presented at the Lepton-Photon Conference at Cornell University in August 1983 [Tu 83]. The individual results on line positions and branching ratios are listed in table 5.1. For comparison, the line positions are also shown in fig. 5.1. For the two lower lines the data of all experiments are in good agreement with each other. The weighted average over the individual measurements including both statistical and systematic errors gives line positions at (108.9 ± 0.8) MeV and (129.0 ± 0.6) MeV. The third line is only observed in the ARGUS and CUSB inclusive photon spectra. However, the statistical significance is not very large in both experiments, showing only a 1.8σ and 2.6σ effect, respectively. In the CB and CLEO spectra no signal is observed, only two bins around 155 MeV are slightly higher than the background. However, CLEO has published a position for the third line at 158 MeV, whereas the CB only has quoted a range of 140-170 MeV⁺). The

⁺) Meanwhile, by analyzing a larger data sample the CB has also observed a third line around 160 MeV [Vl 84].

Table 5.1 Summary of all experimental results on T' photon decays

$2^3S_1 \rightarrow \gamma 1^3P_2$				
Experiment	E_γ [MeV]	inc.BR [%]	Sig(σ) inc. exc.	Product BR exc [%]
ARGUS (inc)	$111.4 \pm 2.0 \pm .6$	$5.6 \pm 2.8 \pm 1$	2.0	---
Crystal Ball (inc)	$108.3 \pm 1.0 \pm 3$	$6.3 \pm 1.3 \pm 1.4$	4.9	
(exc)	$102.0 \pm 2.0 \pm 5$		14	
CLEO (inc)	$109.5 \pm 0.7 \pm 1$	$10.2 \pm 1.8 \pm 2.1$	5.7	1.3 ± 0.4
CUSB (inc)	$108.2 \pm 0.3 \pm 2$	$6.1 \pm 1.4 \pm 2$	4.4	
(exc)	$106.1 \pm 2.6 \pm 1$		15	
Average	108.9 ± 0.8	6.9 ± 1.2		
$2^3S_1 \rightarrow \gamma 1^3P_1$				
ARGUS (inc)	$129.5 \pm 0.6 \pm .6$	$7.9 \pm 2.2 \pm 2.4$	3.6	---
Crystal Ball (inc)	$127.5 \pm 1.3 \pm 1.4$	$6.0 \pm 1.3 \pm 1.4$	4.6	
(exc)	$127.0 \pm 2.0 \pm 5$		15	
CLEO (inc)	$129.0 \pm 0.8 \pm 1$	$8.0 \pm 1.7 \pm 1.6$	4.7	1.9 ± 0.4
CUSB (inc)	$128.1 \pm 0.4 \pm 3$	$5.9 \pm 1.4 \pm 2$	4.2	
(exc)	$128.3 \pm 1.6 \pm 1$		23	
Average	129.0 ± 0.6	6.7 ± 1.2		
$2^3S_1 \rightarrow \gamma 1^3P_0$				
ARGUS (inc)	$148.5 \pm 1.5 \pm .8$	$2.7 \pm 1.5 \pm .8$	1.8	
Crystal Ball (inc)	140 - 170	<4.5	<1	
(exc)	---			
CLEO (inc)	$158.0 \pm 7.0 \pm 1$	$4.4 \pm 2.3 \pm .9$	1.9	
CUSB (inc)	$149.4 \pm 0.7 \pm 5$	$3.5 \pm 1.4 \pm 2$	2.5	
(exc)	---			
Average	149.1 ± 1.6	3.3 ± 1.2		
$1^3P_J \rightarrow \gamma 1^3S_1$				
Crystal Ball (inc)	~426	$3.6 \pm 0.9 \pm .8$		
CUSB (inc)	$427 \pm 1 \pm 5$	$4.0 \pm 1.0 \pm 2$		

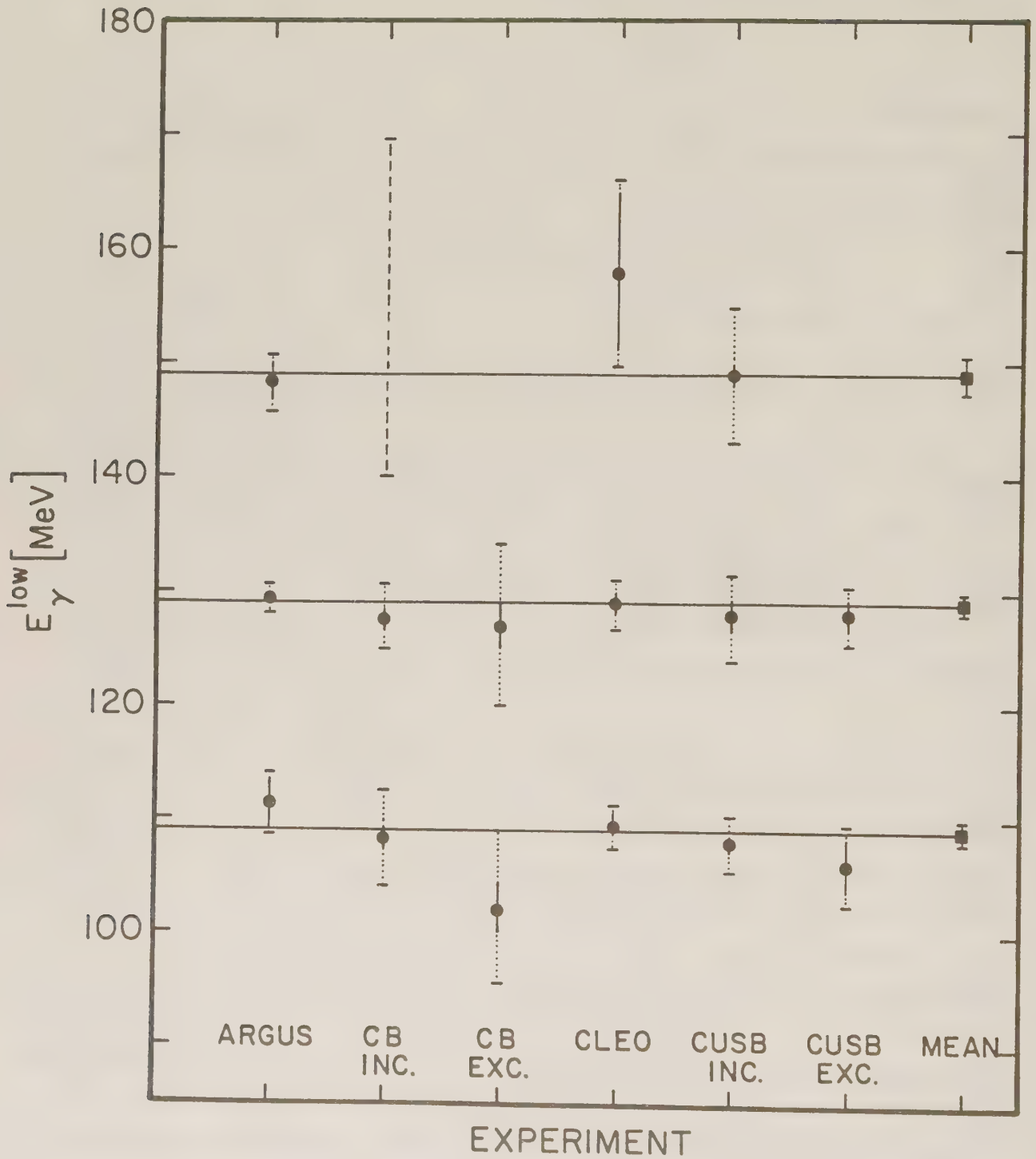


Fig. 5.1 A comparison of the line positions observed by different experiments in the inclusive and exclusive photon spectra from radiative T' decays. The solid error bars give the statistical errors, the dotted bars show the systematic uncertainties. The solid lines give the weighted averages over all measurements.

weighted average of the ARGUS, CLEO, and CUSB data yields a position at (149.1 ± 1.6) MeV. Because of the large statistical errors and the systematic uncertainties in the background subtraction we consider the individual results not to be inconsistent.

The branching ratios $BR(\Upsilon' \rightarrow \gamma \chi_b)$ of all four experiments are also in good agreement with each other. The CLEO data are somewhat larger, but within the errors consistent with the other results. The results for the mirror lines being observed at ~ 426 MeV in the CB spectrum are in good agreement with the CUSB data, as shown in table 5.1. ARGUS and CLEO cannot observe the mirror lines with the present statistics since the expected signal from $\chi_b \rightarrow \gamma \Upsilon$ is of the same order as the background fluctuations.

From the average values of the line positions one determines the masses of the χ_b states to be at $M(1^3P_2) = (9914 \pm 1)$ MeV, $M(1^3P_1) = (9894 \pm 1)$ MeV, and $M(1^3P_0) = (9873 \pm 2)$ MeV. For the cog we calculate $M(1^3P_{\text{cog}}) = (9903 \pm 1)$ MeV.

V.2 Comparison of Experimental Data with Theoretical Predictions

In chapter II we have seen that potential models have been very successful in predicting leptonic widths and masses of 3S states in the $b\bar{b}$ system. Now we can also test predictions for masses of 3P states, 3P -state fine splittings, and E1 transitions rates.

V.2.1 Masses of 3P -States

Table 5.2 lists several predictions for the masses of 3P_J states⁺⁾ . The spin averaged center-of-gravities for 1^3P and 2^3P -states are shown together with the masses of 3S states in a level diagram in fig. 5.2, where the horizontal axis shows the predictions of the individual models. The experimental data are represented by the solid lines. The dashed and dashed-dotted lines indicate the 5% limits of the energy eigenvalue. Most of the potential models predict the eigenvalues for the 1^3P and 2^3P center-of-gravities correctly within 5% and 2%, respectively. Predictions from the phenomenological models are not very good. While the predictions for 2^3P_{cog} are still consistent with measurements, the predicted masses for the 1^3P_{cog} are systematically too low. However, QCD inspired potential

⁺⁾ In principle we list the masses quoted by the authors. If, however, the mass of the Υ' or Υ'' was used as an input we have scaled the 3P -masses according to $M_{\text{exp}}(\Upsilon')/M_{\text{model}}(\Upsilon')$.

Table 5.2 Theoretical predictions for masses of 1^3P_J and 2^3P_J states in the $b\bar{b}$ system. Masses are in MeV.

Model	1^3P_0	1^3P_1	1^3P_2	$1P_{cog}$	2^3P_0	2^3P_1	2^3P_2	$2P_{cog}$	[ref]
BR	-----	-----	-----	9899	-----	-----	-----	-----	[BR 78]
Sterling	-----	-----	-----	9896	-----	-----	-----	10271	[St 78]
Beavis	9821	9845	9868	9855	10221	10238	10255	10246	[Bs 79]
Richardson	-----	-----	-----	9896	-----	-----	-----	10250	[Rn 79]
Cornell	-----	-----	-----	9926	-----	-----	-----	10276	[Ei 80]
Voloshin 1)	-----	-----	-----	9835	-----	-----	-----	-----	[Vo 80]
Baake ²⁾ A	9935	9965	9987	9974	10282	10304	10324	10312	[Ba 81]
B	9960	9991	10015	10000	10295	10325	10348	10334	
Bertlmann ¹⁾	-----	-----	-----	9803	-----	-----	-----	-----	[Bn 81]
BT	-----	-----	-----	9890	-----	-----	-----	10250	[BT 81]
EF	9891	9916	9942	9928	10249	10267	10285	10275	[EF 81]
Buchmüller A	9835	9876	9907	9889	10207	10239	10263	10250	[Bu 81]
Krasemann	9896	9926	9950	9936	10232	10262	10282	10271	[Kr 81]
Kuang, Yan	-----	-----	-----	9920	-----	-----	-----	10270	[KY 81]
Martin ³⁾	-----	-----	-----	9861	-----	-----	-----	10242	[Ma 81]
QR ³⁾	-----	-----	-----	9891	-----	-----	-----	10249	[QR 81]
Barik, Jena	9837	9855	9871	9862	-----	-----	-----	-----	[BJ 82]
Buchmüller B	9859	9881	9897	9887	10226	10244	10258	10250	[Bu 82]
Khare ³⁾	9843	9867	9879	9871	-----	-----	-----	-----	[Kh 81]
MB ⁴⁾	9867	9916	9938	9923	10221	10261	10280	10267	[MB 82]
Gupta ⁴⁾	9868	9893	9910	9900	10232	10252	10266	10258	[Gu 83]
Hagiwara	-----	-----	-----	9900	-----	-----	-----	10256	[Ha 83]
Kang ⁴⁾	9832	9855	9867	9859	10234	10255	10267	10259	[Ka 83]
Kühn, Ono A	-----	-----	-----	9896	-----	-----	-----	10249	[KO 83]
B	-----	-----	-----	9865	-----	-----	-----	10236	
MR ⁴⁾	9880	9906	9917	9909	10240	10260	10268	10262	[MR 83]
CUSB	9873 ±5	9894 ±2	9915 ±2	9904 ±2	10233 ±5	10256 ±2	10271 ±2	10262 ±2	
Experiment (average)	9873 ±2	9894 ±1	9914 ±1	9903 ±1					

1) Predictions from QCD sum rules (S)

2) Bag model calculations (B)

3) Phenomenological models (P)

4) Potential model calculations with spin-independent relativistic corrections (R)

The other predictions are based on non-relativistic potential models (Q).

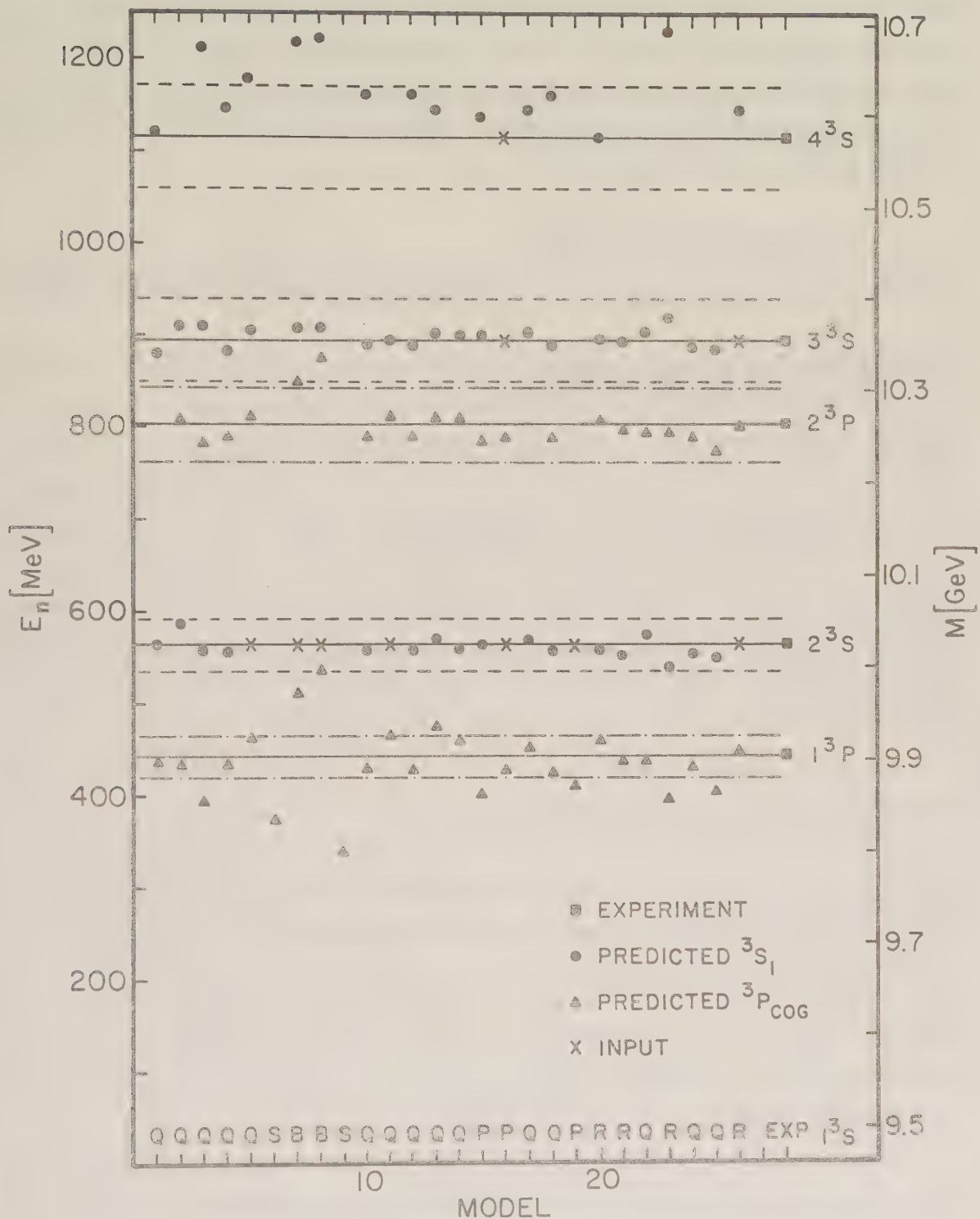


Fig. 5.2 A level diagram for different theoretical predictions for masses of ³S and ³P bb states. The solid lines indicate the observed masses. The dashed and dashed-dotted lines show the 5% limit on the energy eigenvalue. The numbers shown in the horizontal axis correspond to the models listed in table 5.2. The letters label the different classes of models: P: phenomenological potential models, Q: QCD inspired non-relativistic potential models, R: potential models including spin-independent relativistic corrections, S: QCD sum rules, and B: bag model calculations.

models are more successful. For example in the BT model predictions for the 1^3P_{cog} (2^3P_{cog}) energy eigenvalues agree with measurements within 3% (2%). This can be further improved by ~1% if one scales the masses such that the predicted mass M_{pp} , coincides with the experimental value. Except for the Kang model the best predictions are obtained from potential models that include spin-independent relativistic corrections. Examples are the models by Moxhay-Rosner (MR) and Gupta.

V.2.2 Fine Splitting of 3P -States

The fine splitting of $q\bar{q}$ 3P states is usually characterized by:

$$\Delta E_{\text{FS}}(n) := M(n^3P_2) - M(n^3P_0) \quad (5.1a)$$

and the ratio:

$$r_n := [M(n^3P_2) - M(n^3P_1)] / [M(n^3P_1) - M(n^3P_0)] \quad (5.1b)$$

Using eqs. (2.30) we can relate both quantities to the expectation values for the spin-orbit and tensor interactions, a_n and b_n , as defined in eqs. (2.28) and (2.29), yielding:

$$\Delta E_{\text{FS}}(n) = 3a_n + (18/5)b_n \quad (5.2a)$$

$$r_n = [2 - (12/5) \cdot b_n/a_n] / [1 + 6 \cdot b_n/a_n] \quad (5.2b)$$

Note that ΔE_{FS} depends linearly on α_s , since both a_n and b_n depend linearly on the strong coupling constant, whereas r_n is nearly independent of α_s .

Fig. 5.3 shows several predictions for the total splittings $\Delta E_{\text{FS}}(n)$ and the ratios r_n in comparison to the measured quantities for both 3P states. The corresponding predictions for the expectation values a_n and b_n are plotted in fig. 5.4. The individual values are listed in table 5.3.

The predicted splittings ΔE_{FS} are in the range of 34-72 MeV for the 1^3P -states and 27-56 MeV for the 2^3P -states, while from the measured 3P -masses we determine these splittings to be (40.7 ± 1.8) MeV and (38 ± 6) MeV, respectively. Buchmüller has pointed out that a rather large fine splitting is predicted if the fine structure coupling constant scales like the effective Coulomb coupling constant $\mathcal{K}$ in the Cornell model [Bu 82], i.e.:

$$\alpha_s^{\text{FS}}(\mathbf{T}) / \alpha_s^{\text{FS}}(\Psi) = \mathbf{k}(\mathbf{T}) / \mathbf{k}(\Psi) = .48 / .52 = .92 \quad (5.3a)$$

Assuming such a scaling behavior the Buchmüller model predicts splittings of $\Delta E_{\text{FS}}(1)=72$ MeV and $\Delta E_{\text{FS}}(2)=56$ MeV (data set A). Similar large values of 71 MeV and 59 MeV have been obtained in the MB model using the scaling law of eq. (5.3a). On the other hand a much smaller fine splitting is expected if the fine structure coupling constant scales according to perturbative QCD, ie:

$$\alpha_s^{\text{FS}}(\mathbf{T}) / \alpha_s^{\text{FS}}(\Psi) = \ln(m_c^2 / \Lambda_{\overline{\text{MS}}}^2) / \ln(m_b^2 / \Lambda_{\overline{\text{MS}}}^2) \quad (5.3b)$$

which gives .52 for typical values of $m_c=1.48$ GeV, $m_b=4.87$ GeV and $\Lambda_{\overline{\text{MS}}}=400$ MeV. Assuming a scaling according to perturbative QCD, Buchmüller derives the splitting to be 38 MeV and 32 MeV, respectively (data set B). In the Gupta model similar values of 42 MeV and 34 MeV have been calculated using eq. (5.3b). For both models the predictions are in good agreement with measurements indicating that the experimental data seem to favor a scaling according to perturbative QCD, ruling out the scaling behavior of eq. (5.3a). For the other models we note the following tendency. While predictions from earlier models in general give too large splittings, more recent calculations -- which have been done after the χ_b' states were found -- are in the correct range.

Predictions for the ratios r_n range from $\sim .4$ to ~ 1 . The measurement provides a quantitative test of the flux tube model which gives $r_n \sim 0.75$. From the observed ^3P masses we evaluate $r_1 = 1 \pm 0.1$ and $r_2 = 0.7 \pm 0.2$. Due to the large experimental uncertainties r_2 is consistent with all predictions. However, excellent agreement is found for predictions obtained by Buchmüller and Gupta, thus supporting the flux tube model. On the other hand r_1 seems to favor the predictions of the Eichten model which differs from the flux tube model by an opposite sign in the long range component of the spin-orbit interaction. But r_1 is also still consistent with predictions around .7, whereas values $< .6$ seem to be unlikely. However, in order to confirm or rule out the flux tube model more accurate measurements are necessary. The measurement of the hyperfine splitting provides an additional test. Since according to the flux tube model the spin-spin forces only contain the short range potential, one expects perturbative QCD to give accurate results.

Table 5.3 Predictions for fine splittings of 1^3P_J and 2^3P_J states in the $b\bar{b}$ system.

The expectation values for the fine splittings ΔE_{FS} , the spin-orbit interaction a_n and the tensor interactions b_n are in MeV.

Model	ΔE_{FS}	1^3P -state			ΔE_{FS}	2^3P -state			[ref]
		r_1	a_1	b_1		r_2	a_2	b_2	
Beavis	47	23/24=.96	13.6	1.7	34	17/17=1.0	9.9	1.2	[Bs 79]
Baake	A 52	22/30=.73	14.2	2.6	46	20/26=.77	12.7	2.2	[Ba 81]
	B 55	24/31=.79	15.1	2.6	53	23/30=.77	14.6	2.6	
Buchmüller A	72	31/41=.76	19.8	3.5	56	24/32=.75	15.3	2.8	[Bu 81]
EF	51	26/25=1.04	15.0	1.7	36	18/18=1.0	10.5	1.3	[EF 81]
Krasemann	54	24/30=.8	15.0	2.5	50	20/30=.67	13.3	2.8	[Kr 81]
Barik, Jena	34	16/18=.89	9.7	1.4	--	---	--	--	[BJ 82]
Buchmüller B	38	16/22=.73	10.3	1.9	32	14/18=.78	8.8	1.5	[Bu 82]
Khare	36	12/24=.5	9.0	2.5	--	---	--	--	[Kh 81]
MB	71	22/49=.45	17.3	5.3	59	19/40=.48	14.6	4.2	[MB 82]
Gupta	42	17/25=.68	11.3	2.3	34	14/20=.7	9.2	1.8	[Gu 83]
Kang	35	12/23=.52	8.8	2.4	33	12/21=.57	8.5	2.1	[Ka 83]
MR	37	11/26=.42	8.9	2.8	27	8/19=.42	6.5	2.1	[MR 83]
CUSB	42 ± 5	20.9/21.5=1 $\pm .2$	12.3 ± 1.3	1.5 $\pm .7$	38 ± 6	15.4/22.9=.7 $\pm .2$	10.2 ± 1.6	2.1 ± 1.0	
Experiment (average)	40.7 ± 1.8	20.3/20.4=1.0 $\pm .1$	11.9 $\pm .8$	1.4 $\pm .5$					

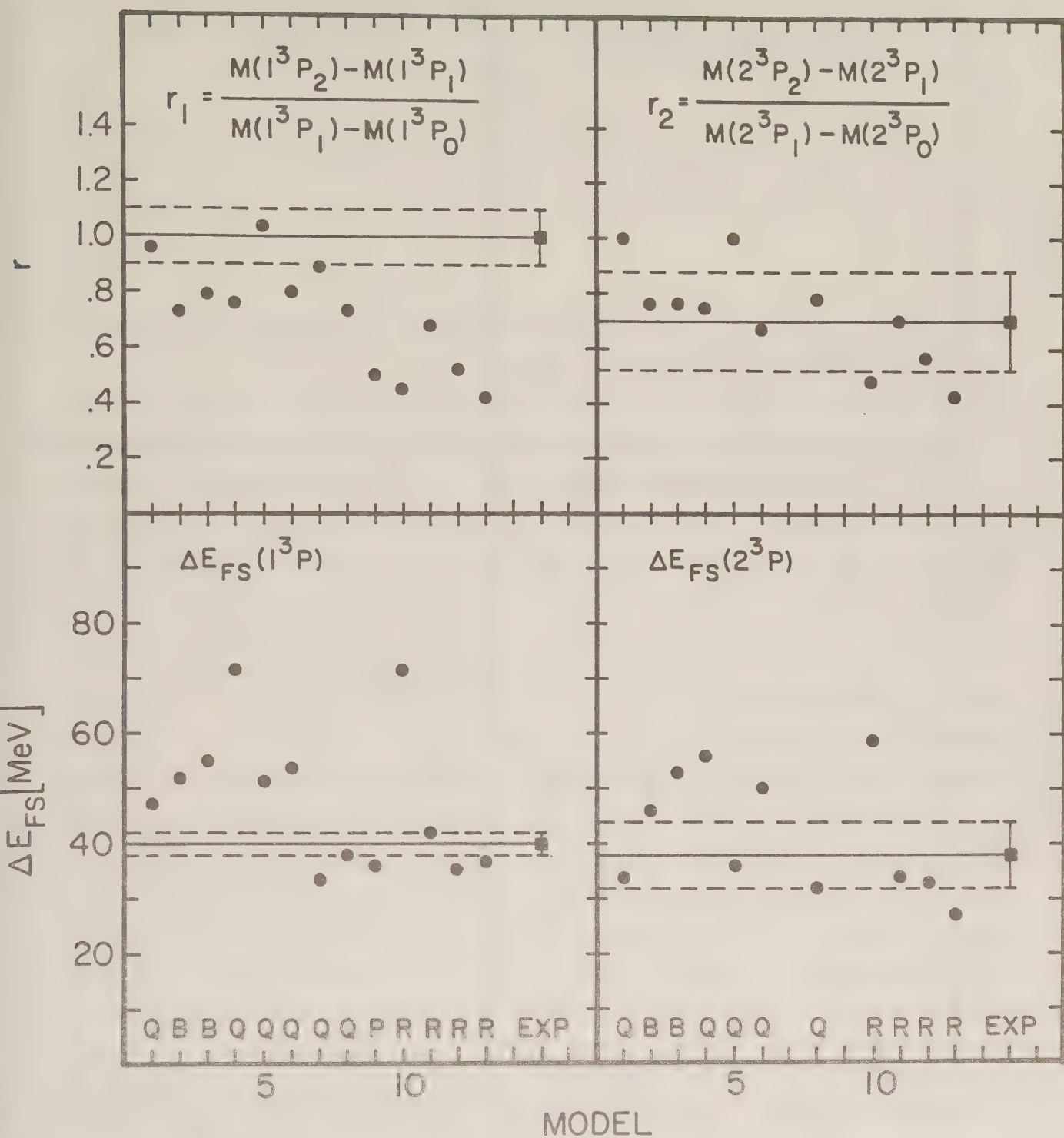


Fig. 5.3 Theoretical predictions of the fine splitting and ratio r for 1³P and 2³P states. The solid lines represent the measured quantities, the dashed lines indicate the error bars. The numbers shown in the horizontal axis correspond to the models listed in table 5.3. The letters indicate the class of model (see figure 5.2).

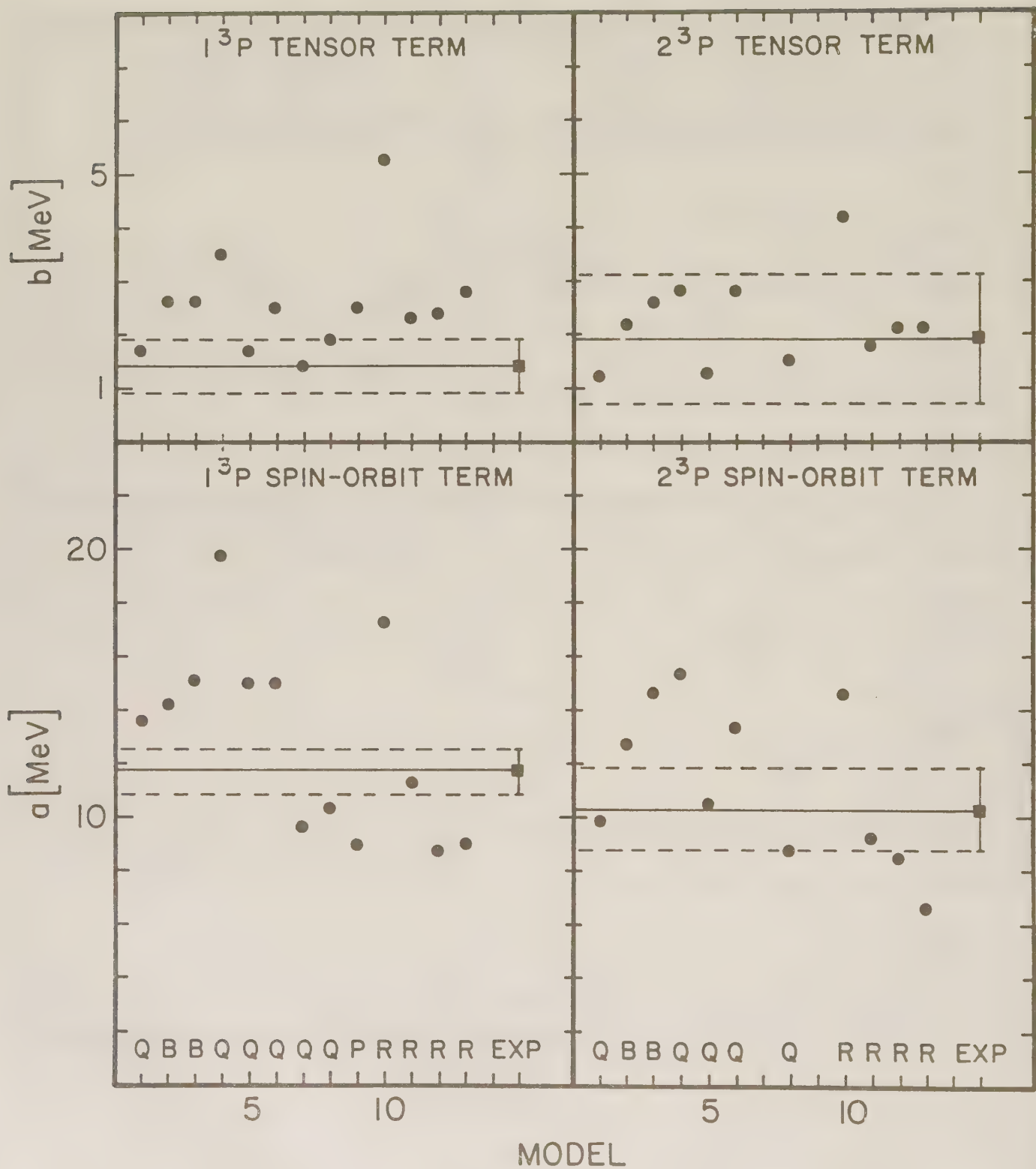


Fig. 5.4 Theoretical predictions of the spin-orbit and tensor interaction for 1^3P and 2^3P states. The solid lines represent the measured quantities, the dashed lines indicate the error bars. The numbers shown in the horizontal axis correspond to the models listed in table 5.3. The letters again indicate the class of model.

The best predictions for the expectation values a_n and b_n for both 3P states are again given by the Buchmüller and Gupta models. However, both the spin-orbit and tensor terms depend linearly on α_s . We note the following tendency. Earlier models in general overestimate both a_n and b_n . Except for the MB model which predicts too large spin-orbit and tensor interactions, more recent models generally underestimate a_n while b_2 is predicted correctly and b_1 is slightly overestimated. Further tests of the different models will be provided by measuring the fine splitting in 3D states [Ei 83].

V.2.3 E1 Transition Rates and Reduced Widths

Table 5.4 lists some predictions for the transition rates $\Gamma_{E1}(2^3S_1 \rightarrow \gamma 1^3P_J)$ and $\Gamma_{E1}(3^3S_1 \rightarrow \gamma 2^3P_J)$ in the $b\bar{b}$ system. The two columns on the left side show the E1-rates quoted by the individual models. The numbers in brackets give the entire rates for χ_b and χ_b' production, respectively. However, since the E1 transition rates depend very strongly on the photon energy we have adjusted them for comparison to the observed photon energies using eq. (2.36). The rates obtained in this way for each model are shown in the columns on the right side where we have summed over the individual spin components. The experimental values for Γ_{E1} are obtained from the observed total widths $\Gamma_{tot}(T') = (33.9 \pm 3.4)$ keV, $\Gamma_{tot}(T'') = (26.3 \pm 4)$ keV (see appendix A) and the measured inclusive BR's quoted in table 5.1 for $T' \rightarrow \gamma \chi_b$ and in eqs. (4.27-4.28) for $T'' \rightarrow \gamma \chi_b'$.

Fig. 5.5 shows the adjusted theoretical rates in comparison to the measured data, represented by the solid lines. The dashed lines indicate the errors on the measurements. For $\Gamma(2^3S_1 \rightarrow \gamma 1^3P)$ most of the models predict values between 4.8 keV and 5.6 keV which are in excellent agreement with the observed rate of (5.7 ± 1) keV. Only two predictions are substantially lower. For $\Gamma(3^3S_1 \rightarrow \gamma 2^3P)$ the predicted rates are slightly lower than the measured value. Most models predict rates around 6.5 keV compared to a measured rate of (9.4 ± 2.5) keV. However, due to the large experimental error these numbers are not inconsistent. The best predictions of E1 rates for both transitions are obtained from the Moxhay-Rosner model.

The reduced widths are determined by:

$$\Gamma_r(^3S_1 \rightarrow \gamma ^3P_J) := \Gamma_{E1}(^3S_1 \rightarrow \gamma ^3P_J) / [k_\gamma^3 (2J+1)] \quad (5.4)$$

where k_γ is the CM photon energy. By convention one quotes just the ratios:

Table 5.4 Predictions for E1 transition rates in the $b\bar{b}$ system.
All rates are in keV.

Model	$\Gamma(2^3S_1 \rightarrow \gamma 1^3P_J)$ J=0 , 1 , 2			$\Gamma(3^3S_1 \rightarrow \gamma 2^3P_J)$ J=0 , 1 , 2			$\Gamma(2S \rightarrow \gamma 1P)$ adjusted	$\Gamma(3S \rightarrow \gamma 2P)$ adjusted	[ref]
Sterling	(8.7)			(7.2)			(4.6)	(6.4)	[St 78]
Cornell	(2.4)			(4.5)			(5.4)	(6.6)	[Ei 80]
Baake	A	0.22	.19 .08	.47	.49	.25	(5.2)	(5.6)	[Ba 81]
	B	0.09	.04 .001	.31	.20	.04	(6.1)	(6.0)	
BT	(6.2)			(7.7)			(5.2)	(6.6)	[BT 81]
Buchmüller A	2.0	2.7	2.2	2.4	3.4	2.7	(5.0)	(6.5)	[Bu 81]
Krasemann	(1.6)			(3.0)			(5.2)	(6.5)	[Kr 81]
QR	(6.3)			(8.4)			(5.1)	(6.6)	[QR 81]
Barik, Jena	1.56	3.5	4.38	---	---	---	(3.6)	---	[BJ 82]
Buchmüller B	1.3	2.4	2.8	1.6	3.0	3.3	(5.6)	(6.4)	[Bu 82]
Khare	0.56	1.06	1.6	---	---	---	(3.0)	---	[Kh 81]
MB	0.78	1.01	.96	1.3	1.9	1.8	(4.9)	(5.8)	[MB 82]
Kang	1.4	2.8	3.6	2.2	4.3	5.3	(4.7)	(5.3)	[Ka 83]
Kühn, Ono	A	(5.2)		(7.3)			(5.4)	(6.8)	[KO 83]
	B	(7.4)		(8.9)			(4.4)	(5.9)	
MR	1.0	2.1	2.2	1.4	2.8	2.7	(5.4)	(6.9)	[MR 83]
CUSB	1.2 ±.6	2.0 ±.7	2.0 ±.7	2.0 ±1.6	4.1 ±2.0	3.3 ±1.9	5.2 ±1.2	(9.4 ±2.5)	
Experiment	1.1 ±.5	2.3 ±.6	2.3 ±.6				(5.7 ±1.0)		

The first two columns show the individual rates quoted by the authors, where the values in brackets refer to the entire rates. The columns denoted by adjusted show the entire rates adjusted to the measured photon energies.

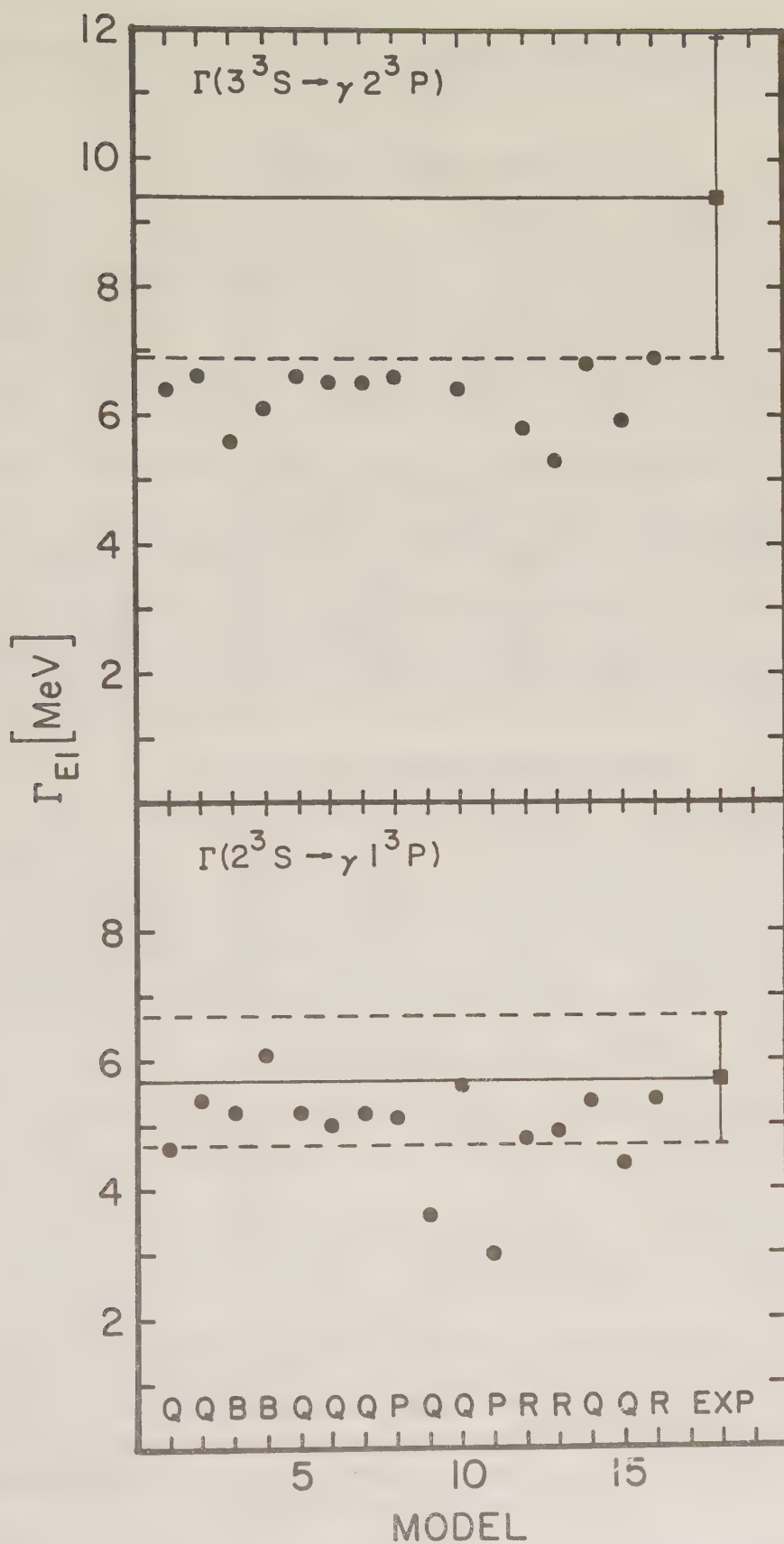


Fig. 5.5 Theoretical predictions for E1 transition rates. The solid lines show the observed rates, the dashed lines indicate the error bars. The numbers shown in the horizontal axis correspond to the models listed in table 5.4. The letters indicate the class of model.

Table 5.5 Predicted product branching ratios for exclusive cascades.
All values are in percent.

BR($3^3S_1 \rightarrow \gamma 2^3P_J$) x BR($2^3P_J \rightarrow \gamma 2^3S_1$)					
Model	J=0	J=1	J=2	sum	
Buchmüller	.13 (2.2)	1.7 (17.5)	1.06 (11.5)	2.9	
Cornell	.09 (1.6)	1.27 (13.0)	0.83 (8.5)	2.2	
MB	.10 (2.5)	1.37 (15.6)	0.84 (8.5)	2.3	
MR	.11 (2.1)	1.65 (15.3)	1.01 (9.7)	2.8	
Experiment	<2.2 (<29)	3.5±1.8 (22±13)	1.5±0.9 (12±8)	5.0±2.2	
BR($3^3S_1 \rightarrow \gamma 2^3P_J$) x BR($2^3P_J \rightarrow \gamma 1^3S_1$)					
Buchmüller	.09 (1.5)	0.94 (9.7)	0.52 (5.7)	1.6	
Cornell	.11 (1.8)	1.14 (11.7)	0.65 (6.7)	1.9	
MB	.02 (0.4)	0.88 (10.0)	0.83 (8.4)	1.7	
MR	.08 (1.4)	1.40 (13.0)	0.88 (8.5)	2.4	
Experiment	<.7 (<9)	2.6±1.0 (17±8)	1.0±.5 (8±5)	3.6±1.2	
BR($2^3S_1 \rightarrow \gamma 1^3P_J$) x BR($1^3P_J \rightarrow \gamma 1^3S_1$)					
Buchmüller	.14 (4.4)	2.60 (41.3)	1.19 (18.4)	3.9	
Cornell	.10 (3.0)	2.05 (32.3)	0.85 (13.3)	3.0	
MB	.09 (3.9)	2.25 (38.2)	1.05 (15.8)	3.4	
MR	.13 (4.4)	2.5 (40.5)	1.15 (17.7)	3.8	
Experiment	<.38	1.9±.4 (32±12)	1.3±.4 (21±8)	3.2±.6	
BR($3^3S_1 \rightarrow \gamma 1^3P_J$) x BR($1^3P_J \rightarrow \gamma 1^3S_1$)					
Buchmüller	.0002	.0048	.0035	.0083	
Cornell	.018	.51	.31	.838	
MB	--	--	--	--	
MR	.004	.034	.103	.141	
Experiment	--	--	--	<1.3	

The numbers in brackets show the BR's for $n^3P_J \rightarrow \gamma n'^3S_1$. To obtain the BR's we used the measured total widths $\Gamma_{\text{tot}}(\mathbf{T}') = 34$ keV, $\Gamma_{\text{tot}}(\mathbf{T}'') = 26$ keV and calculated hadronic widths $\Gamma_{\text{had}}(1^3P_{0,1,2}) = (668, 50, 178)$ keV and $\Gamma_{\text{had}}(2^3P_{0,1,2}) = (534, 68, 147)$ keV obtained from [KY 81] with $\alpha_s = .16$. The theoretical E1-transition rates have been adjusted to the measured photon energies. The experimental values for the sum only include the J=1 and J=2 contributions.

$$\Gamma_r(^3S_1 \rightarrow \gamma ^3P_2) : \Gamma_r(^3S_1 \rightarrow \gamma ^3P_1) : \Gamma_r(^3S_1 \rightarrow \gamma ^3P_0) \quad (5.5)$$

normalizing the individual reduced widths to the width for the $J=1$ transitions. Non-relativistic potential models predict these ratios to be 1:1:1. In potential models which include spin-independent relativistic correction the ratios slightly change. For example the Moxhay-Rosner model predicts 1.05:1:0.88 and 1.04:1:0.9 for the transitions $2^3S_1 \rightarrow \gamma 1^3P_J$ and $3^3S_1 \rightarrow \gamma 2^3P_J$. The corresponding ratios determined from the measured E1 rates are $(1.02 \pm 0.25):1:(0.96 \pm 0.36)$ and $(0.8 \pm 0.4):1:(0.79 \pm 0.5)$, being in good agreement with predictions from both types of models.

V.2.4 Product Branching Ratios for Exclusive Photon Cascades

Table 5.5 lists a few predictions of product branching ratios for the exclusive reactions in comparison to our measurements. Since the authors have quoted only E1 transition rates we have obtained the theoretical product branching ratios by the following procedure:

- i) We have adjusted the individual E1 transition rates to the observed photon energies.
- ii) To evaluate the branching fractions $BR(n^3S_1 \rightarrow \gamma n'^3P_J)$ we have used the measured total widths $\Gamma_{tot}(T')=34$ keV and $\Gamma_{tot}(T'')=26$ keV for normalization.
- iii) In order to determine the branching ratios $BR(n^3P_J \rightarrow \gamma n'^3S_1)$ we have modelled the hadronic widths of the 3P states. Using the formulas in eqs. (5.6) we have scaled the predictions for $\Gamma_{had}(^3P_J)$ given by Kuang and Yan [KY 81] to the observed 3P masses and set $\alpha_s=0.16.^{+}$ From $\Gamma_{had}(^3P_J)$ and the corresponding adjusted E1 transition rates we have calculated $\Gamma_{tot}(^3P_J)$ and $BR(n^3P_J \rightarrow \gamma n'^3S_1)$ for each model, where contributions from transitions into 3D states have been neglected.

For the transitions $T' \rightarrow \gamma \lambda_b \rightarrow \gamma \gamma T$ predicted and measured product branching ratios are in good agreement. The numbers shown in table 5.5 lead to a theoretical intensity ratio of $(.41-.46):1$ for transitions via $J=2$ and $J=1$ 1^3P_J states, which is consistent with the experimental acceptance corrected value of $(0.68 \pm 0.26):1$. For the transitions $T'' \rightarrow \gamma \lambda_b' \rightarrow \gamma \gamma (T \text{ or } T')$ the predictions for the product branching ratios are $\sim 1-2\sigma$ lower than our measurements. This is essentially due to lower predictions both for the

⁺From this procedure we have determined the hadronic widths to be $\Gamma_{had}(1^3P_{2,1,0})=(178, 50, 668)$ keV and $\Gamma_{had}(2^3P_{2,1,0})=(142, 68, 534)$ keV. For the calculation of $\Gamma_{had}(n^3P_1)$ a quark mass of $m_b=5.17$ GeV was used.

E1 rates $\Gamma_{E1}(3^3S_1 \rightarrow \gamma 2^3P_J)$ -- see previous section -- and the branching fractions $BR(2^3P_J \rightarrow \gamma 1^3S_1)$ and $BR(2^3P_J \rightarrow \gamma 2^3S_1)$. The second effect might simply result from modelling too large hadronic widths.⁺) However, the experimental errors are rather large, such that the deviations are only between 1σ and 1.5σ . Therefore the individual predictions are still consistent with our measurements. For the acceptance corrected intensity ratios we obtain $(.42 \pm .33):1$ and $(.38 \pm .24):1$ from the data for $T'' \rightarrow \gamma\gamma T'$ and $T'' \rightarrow \gamma\gamma T$ respectively. This agrees with the corresponding theoretical values of $(.61-.65):1$ and $(.55-.62):1$, except for the MB model which predict the latter ratio to be 0.94. For the transition $T'' \rightarrow \gamma\chi_b \rightarrow \gamma\gamma T$ the individual predictions differ significantly, but unfortunately our statistics are not large enough to test the different models.

V.2.5 Hadronic Widths of 3P -States

Since the 3P -states decay dominantly into hadrons the hadronic widths give the main contribution to the total widths of the 3P -states. To lowest order in α_s the hadronic widths in the $b\bar{b}$ system are predicted to be [Ba 76]:

$$\Gamma_{had}(^3P_2) = (128/5) \alpha_s^2 |R'_P(0)|^2 / M_P^4 \quad (5.6a)$$

$$\Gamma_{had}(^3P_1) = (20/9) (\alpha_s/\pi) \ln[4m_b^2/(4m_b^2 - M_P^2)] \cdot \Gamma_{had}(^3P_2) \quad (5.6b)$$

$$\Gamma_{had}(^3P_0) = (15/4) \cdot \Gamma_{had}(^3P_2) \quad (5.6c)$$

where M_P is the cog mass of the 3P -state, $R'_P(0)$ the derivative of its radial wave function and m_b the b-quark mass. In non-relativistic models $R'_P(0)$ is identical for all three 3P_J -states.

In the charmonium system the total widths of 3P -states are in the MeV range, e.g. $\Gamma_{tot}(^3P_2) \sim 2$ MeV. Since this is comparable with the energy resolution it was possible to extract $\Gamma_{tot}(^3P_J)$ from the measured shape of the photon spectrum, allowing one in turn to determine the hadronic widths [Bl 82]. In the $b\bar{b}$ system, however, these widths are much narrower and therefore not experimentally accessible. On the other hand, if we assume that potential models give correct predictions for $\Gamma_{E1}(m^3P_J \rightarrow \gamma m'^3S_1)$ as they did for $\Gamma_{E1}(n^3S_1 \rightarrow \gamma n'^3P_J)$ we can estimate the hadronic widths from the

⁺) For example a change of α_s from 0.16 to 0.15 reduces the hadronic widths $\Gamma_{had}(n^3P_2)$ by $\sim 14\%$ and $\Gamma_{had}(n^3P_1)$ by $\sim 20\%$. In addition higher order QCD effects on $\Gamma_{had}(n^3P_1)$ are unknown.

measured branching ratios $BR(n^3P_J \rightarrow \gamma m'^3S_1)$ according to:

$$\Gamma_{had}(n^3P_J) = \Gamma_{E1}(J^{++}) [1-B(J^{++})] / B(J^{++}) \quad (5.7)$$

where in case of the 1^3P -states $\Gamma_{E1}(J^{++})$ and $B(J^{++})$ denote the transition rate and BR for $1^3P_J \rightarrow \gamma 1^3S_1$ and in case of the 2^3P -state the rates and BR's for both $2^3P_J \rightarrow \gamma 2^3S_1$ and $2^3P_J \rightarrow \gamma 1^3S_1$. The small contribution from the E1 transition $2^3P_J \rightarrow 1^3D_J$, has been neglected.

Table 5.6 summarizes the results for our measurements obtained by this procedure. For the theoretical Γ_{E1} rates we have used an average over the four model predictions given in table 5.5. The errors quoted result purely from the statistical uncertainties in the measured branching ratios. Considering the large errors the estimated widths are consistent with the predictions given in the previous section.

Table 5.6 Estimated hadronic widths $\Gamma_{had}^{est}(^3P_J)$ of 3P_J states obtained from the CUSB branching ratios and theoretical predictions for E1 rates.

	BR [%]	$\Gamma_{E1}^{a)}$ [keV]	$\Gamma_{had}^{est}(^3P_J)$ [keV]	$\Gamma_{had}^{th}(^3P_J)^{b)}$ [keV]
1^3P_2	21 ± 8	34.8	131 ± 63	178
1^3P_1	32 ± 10	31	66 ± 30	50
2^3P_2	20 ± 9	29	116 ± 68	142
2^3P_1	39 ± 15	24.5	39 ± 25	68

a) an average over the adjusted E1 rates given by [Ei 80, BT 81, MB 82, MR 83].

b) predictions of Kuang and Yan for $\alpha_s=0.16$.

The ratios of hadronic widths can be determined from measurements without any theoretical input. For the 1^3P states one obtains from eqs. (5.7) and (2.36b):

$$\Gamma_{had}(1^3P_0) / \Gamma_{had}(1^3P_2) = k_0^3 / k_2^3 \cdot [B(2^{++}) / B(0^{++})] \cdot [1-B(0^{++})] / [1-B(2^{++})] \quad (5.8a)$$

$$\Gamma_{had}(1^3P_1) / \Gamma_{had}(1^3P_2) = k_1^3 / k_2^3 \cdot [B(2^{++}) / B(1^{++})] \cdot [1-B(1^{++})] / [1-B(2^{++})] \quad (5.8b)$$

where k_J is the photon energy for $1^3P_J \rightarrow \gamma 1^3S_1$. For the 2^3P -states the expressions for these ratios differ slightly since two E1 rates contribute to Γ_{E1} in eq. (5.7). Defining photon energies and BR's for $2^3P_J \rightarrow n^3S_1$ by $k_J(n)$ and $B_n(J^{++})$ one gets: ⁺

$$\Gamma_{\text{had}}(2^3P_0)/\Gamma_{\text{had}}(2^3P_2) = k_0^3(n)/k_2^3(n) \cdot [B_n(2^{++})/B_n(0^{++})] \cdot [1-B(0^{++})]/[1-B(2^{++})] \quad (5.9a)$$

$$\Gamma_{\text{had}}(2^3P_1)/\Gamma_{\text{had}}(2^3P_2) = k_1^3(n)/k_2^3(n) \cdot [B_n(2^{++})/B_n(1^{++})] \cdot [1-B(1^{++})]/[1-B(2^{++})] \quad (5.9b)$$

where $B(J^{++})=B_1(J^{++})+B_2(J^{++})$. All quantities on the right hand side of eqs. (5.8) and (5.9) are measurable in experiments.

Of the two, the first ratio is of greater interest, since it allows for a determination of α_s . Including first order QCD corrections this ratio is predicted to be [Ty 82]:

$$\Gamma_{\text{had}}(1^3P_0)/\Gamma_{\text{had}}(1^3P_2) = 15/4 (1 + 9.5\alpha_s/\pi) \quad (5.10)$$

Unfortunately our statistics are presently not large enough to measure $B(0^{++})$ for both the 1^3P_0 and 2^3P_0 states. Assuming the predicted branching fractions to be correct at least a factor 10 of the present statistics is necessary to observe a clear signal for $B(0^{++})$. The second ratio, which already depends in the lowest order on α_s , can be determined from our present measurements. However, since the first order QCD corrections of $\Gamma_{\text{had}}(1^3P_1)$ are unknown, the determination of α_s is rather unreliable. In addition, due to relativistic corrections $R_p'(0)$ may differ substantially for the individual 3P states as pointed out by McClary and Byers [MB 82]. We therefore quote the results just for completeness. For the ratio in eqs. (5.8b) and (5.9b) we obtain: $\Gamma_{\text{had}}(1^3P_1)/\Gamma_{\text{had}}(1^3P_2)=.50\pm.33$ and $\Gamma_{\text{had}}(2^3P_1)/\Gamma_{\text{had}}(2^3P_2)=.34\pm.32$. Using eqs. (5.6a,b) in the non-relativistic approximation with $m_b=5.17$ GeV this leads to $\alpha_s(\chi_b)=.28\pm.19$ and $\alpha_s(\chi_b')=.11\pm.10$, respectively. Due to the large errors this is consistent with measurements of $\Gamma_{\text{ggg}}(\Upsilon)/\Gamma_{\text{ee}}(\Upsilon)$ yielding $\alpha_s(\Upsilon)=.17\pm.01$ [Ho 83].

⁺) We have neglected relativistic effects, which result in slightly different matrix elements for the individual 3P states in the E1 transition rates (see [MR 83]).

V.2.6 Measurement of the Exponent in an Effective Potential

Quigg and Rosner have pointed out that ratios of level spacing of $q\bar{q}$ states can be related to the exponent ν^{eff} of an effective potential $V_{\text{eff}}(r)=ar^\nu$ [QR 79]. To evaluate ν^{eff} from the observed masses in the Υ and Ψ systems let us consider the following ratios of level spacings:

$$\rho_1 = (E_{2S}-E_{1P})/(E_{2S}-E_{1S}) \quad (5.11a)$$

$$\rho_2 = (E_{3S}-E_{2P})/(E_{3S}-E_{2S}) \quad (5.11b)$$

where E_{nS} denotes the mass of a n^3S state and E_{nP} the cog of a n^3P state. The theoretical predictions for ρ_1 and ρ_2 versus ν^{eff} as obtained by Quigg and Rosner from a non-relativistic calculation with $V_{\text{eff}}(r)=ar^\nu$ [QR 77] are shown in fig. 5.7 in the range $-1 \leq \nu^{\text{eff}} \leq 2$ by the dashed and solid lines.

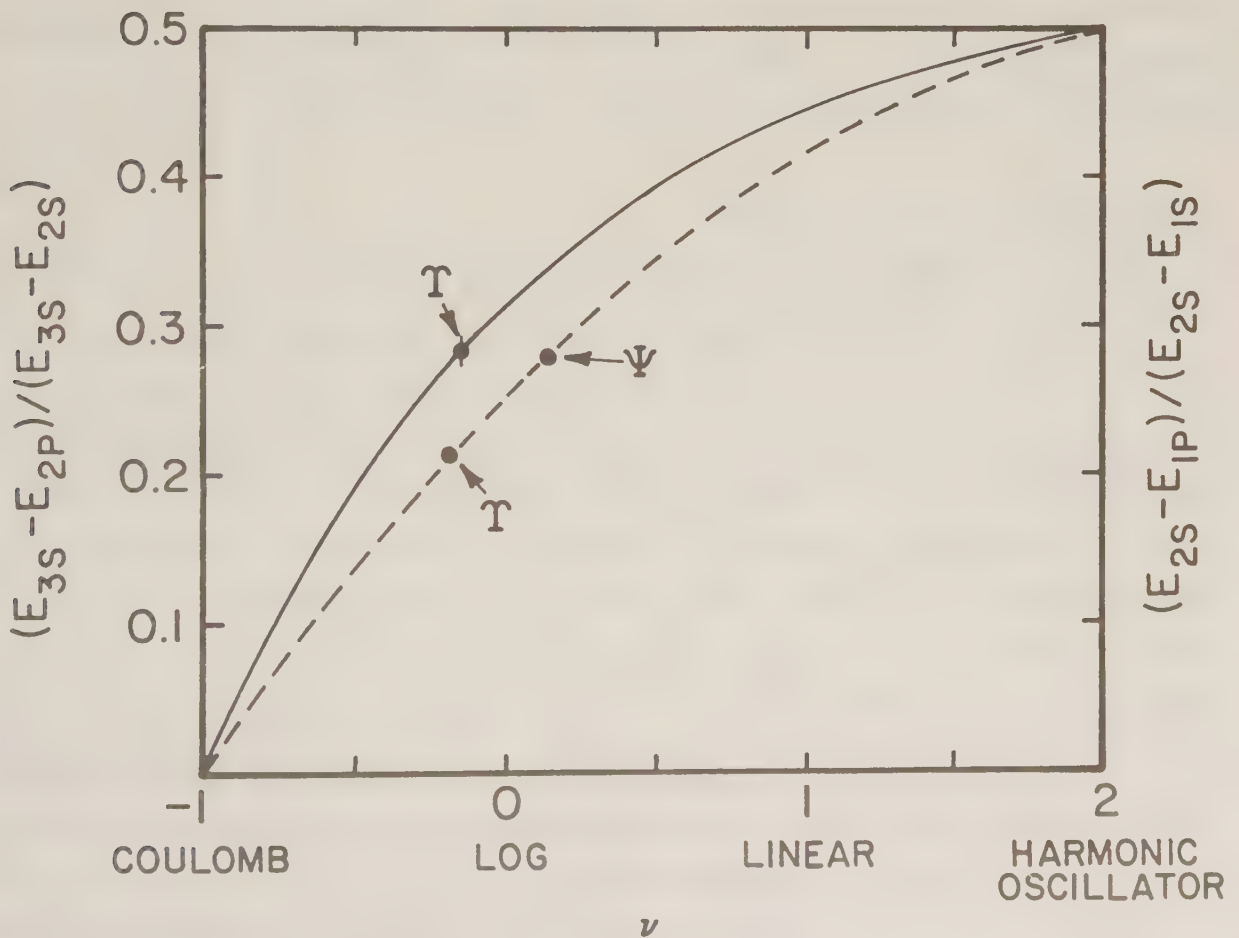


Fig. 5.6 The ratios of level spacings $(E_{3S}-E_{2P})/(E_{3S}-E_{2S})$ (solid line) and $(E_{2S}-E_{1P})/(E_{2S}-E_{1S})$ (dashed line) versus the exponent of an effective potential $V_{\text{eff}}(r)=a \cdot r^\nu$. The solid points represent the measured ratios from Υ and Ψ data.

From the measured masses in the Υ system we determine $\rho_1(\Upsilon)=.214\pm.002$ and $\rho_2(\Upsilon)=.282\pm.004$. As shown in the figure this leads to values of $v_1^{\text{eff}}(\Upsilon)=-.17\pm.01$ and $v_2^{\text{eff}}(\Upsilon)=-.14\pm.03$ for the exponent, respectively. From the observed masses in the Ψ system we evaluate $\rho_1(\Psi)=.277\pm.001$ obtaining in turn a value of $v_1^{\text{eff}}(\Psi)=.14\pm.01$ from the figure.

All three values are rather small indicating that in both systems a logarithmic potential gives a good approximation for $V_{\text{eff}}(r)$. However, the effective potential differs slightly for the Υ and Ψ systems. The negative exponents indicates that in the Υ system the potential is more Coulomb-like, whereas in the Ψ system the potential already shows a tendency to be more linear. Such a behavior is expected for a QCD inspired potential and simply results from different radii of equivalent $b\bar{b}$ and $c\bar{c}$ states (see fig. 2.5). To estimate the change in the effective potential due to this effect let us consider some predictions for $\rho_1(\Psi)/\rho_1(\Upsilon)$ from models that are most explicitly based on QCD. Using the BT and MR models we obtain a ratio $\rho_1(\Psi)/\rho_1(\Upsilon)$ of 1.29 and 1.26, respectively. These predictions are in excellent agreement with the measured value of $1.29\pm.01$. We therefore conclude that the $q\bar{q}$ potential is in fact flavor independent.

V.3 Comparison of χ_b - χ_b' - χ_c States

Table 5.7 shows the measured values for the cog's, transition rates, fine splittings, and ratios of level spacings r_n for the χ -states in the $b\bar{b}$ and $c\bar{c}$ systems. For comparison the range of theoretical predictions has also been listed. Except for the predicted transition rates $\Psi'\rightarrow\gamma\chi_c$ in non-relativistic models, which are a factor of 2.5 higher than measurements, predictions for both systems are very satisfactory. In the $c\bar{c}$ system, however, one expects relativistic effects to become more important. For example McClary and Byers have shown that one can predict realistic E1 transition rates for $\Psi'\rightarrow\gamma\chi_c$ if one includes spin-independent relativistic corrections. Their prediction of 61 keV is rather close to the observed value of (57 ± 2) keV. However, in other relativistic models like the MR model the rate is still approximately a factor of 2 too high. This might be due to non-negligible effects from light quark pair creation, since the Ψ' is already very close to the $D\bar{D}$ threshold.

Table 5.7 shows that observed transition rates and fine splittings are much smaller in the $b\bar{b}$ system and the level spacing is less asymmetric. While in the $c\bar{c}$ system r_1 is $\sim .5$, values of $r_1=1\pm 0.1$ and $r_2=0.7\pm 0.2$ are obtained in the $b\bar{b}$ system.

Table 5.7 Comparison of χ_b - χ_b' - χ_c states.

Property	χ_b	χ_b'	χ_c
Masses for $^3P_{cog}$ [MeV] exp: th:	9903 $\pm$ 1 9861 to 9936	10262 $\pm$ 2 10249 to 10276	3524.9 $\pm$ 0.4 3497 to 3520
E1 rates for $^3S \rightarrow \gamma ^3P$ Γ_{E1} [keV] exp: th:	5.7 $\pm$ 1.0 3.0 to 6.1	9.4 $\pm$ 2.5 5.3 to 6.9	57 $\pm$ 9 61 to 145
ratios of reduced widths for (J=2):(J=1):(J=0) exp: th(NR):a) th(rel):b)	(1.03 $\pm$.25):1:(.96 $\pm$.39) 1:1:1 1.05:1:0.88	(.8 $\pm$.4):1:(.79 $\pm$.5) 1:1:1 1.04:1:0.9	(1.3 $\pm$.1):1:(.95 $\pm$.12) 1:1:1 1.11:1:0.72
total splitting ΔE_{FS} [MeV] exp: th:	40 $\pm$ 2 34 to 72	38 $\pm$ 6 27 to 53	141 $\pm$ 1 134 to 143
ratios of level spacings r exp: th:	1 $\pm$.1 .4 to 1	.7 $\pm$.2 .4 to 1	.47 $\pm$.01 .35 to .6

Theoretical values are based on potential models.

- a) from nonrelativistic potential models
- b) from [MR 83] which includes spin-independent relativistic corrections

V.4 Conclusion

Fig. 5.7 summarizes the experimental results on masses and branching ratios obtained so far in the $b\bar{b}$ system below the $B\bar{B}$ threshold. The values shown for masses of the Υ -states and χ_b states as well as the branching fractions for the inclusive reaction $\Upsilon' \rightarrow \gamma \chi_b$ and for the hadronic transitions are averages over different experiments. All other data are CUSB measurements.

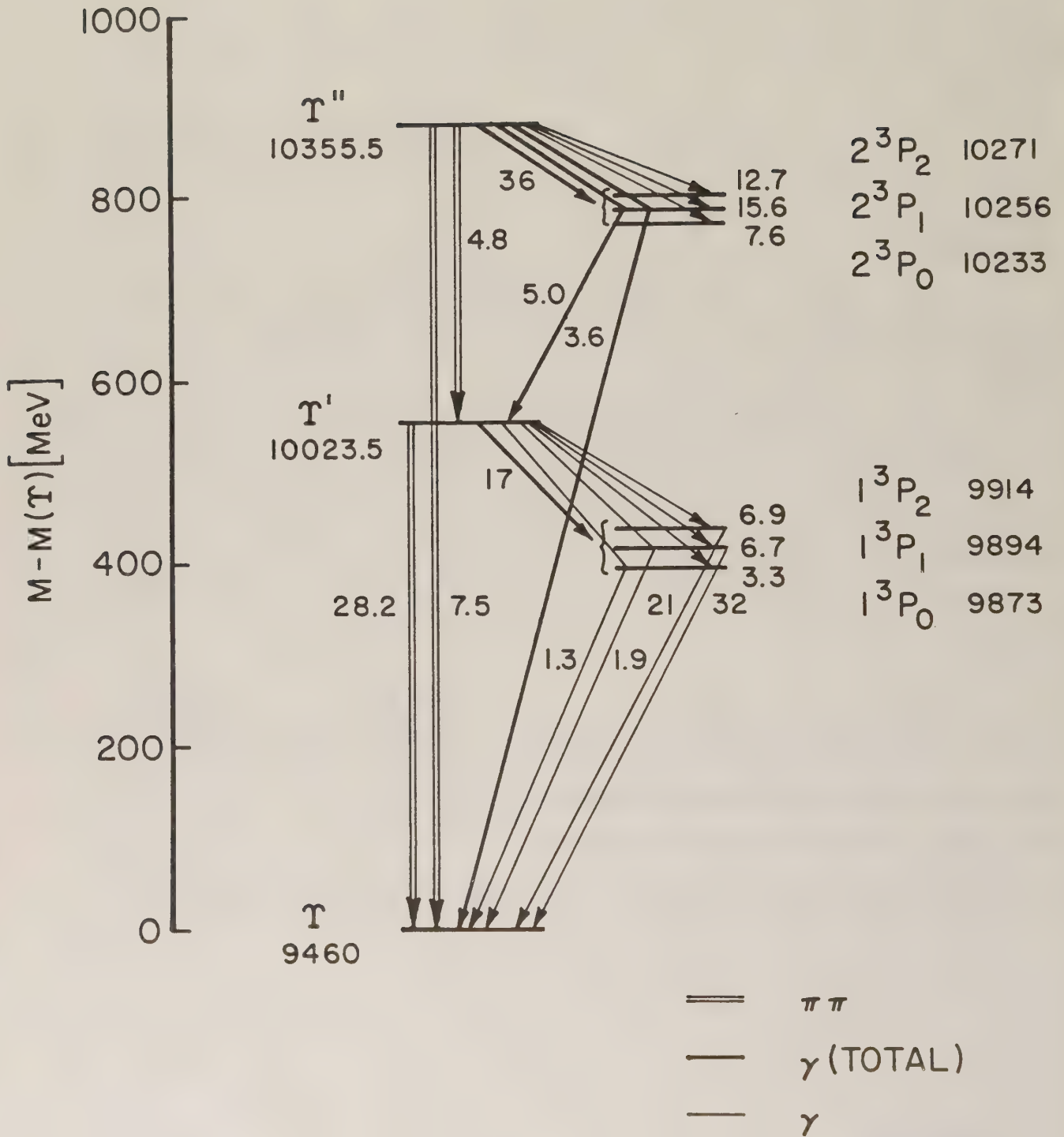


Fig. 5.7 A level diagram summarizing the observed masses for 3S and 3P states and the measured branching fractions in the bottomonium system. The masses are given in MeV, the branching ratios in percent.

We have observed the χ_b states in both the inclusive photon spectrum and exclusive cascade transition. The masses obtained from both analyses for the $J=2$ and $J=1$ χ_b states are in good agreement with each other. The transition via the $J=0$ state is not observed in the present exclusive data sample. The level spacings $M(1^3P_2)-M(1^3P_1)$ and $M(1^3P_1)-M(1^3P_0)$ are nearly equidistant, i.e. $r_1=1.0\pm0.1$. Our measurements for the χ_b masses and branching ratios for the inclusive reaction $\Upsilon'\rightarrow\gamma\chi_b$ are in good agreement with the results of other experiments.

We have also observed the χ_b' states in both the inclusive photon spectrum and exclusive cascade transitions. However, the individual lines are not fully resolved. For the time being these measurements are the only experimental data on the χ_b' states. In the exclusive data sample again the transition via the $J=0$ state is not observed. For the masses of $J=2$ and $J=1$ χ_b' states the results from both analyses are in good agreement with each other. The fine splitting $M(2^3P_2)-M(2^3P_0)$ is smaller than $M(1^3P_2)-M(1^3P_0)$. In addition the individual level spacings $M(2^3P_2)-M(2^3P_0)$ and $M(2^3P_1)-M(2^3P_0)$ are not equidistant, observing a larger value for $M(2^3P_1)-M(2^3P_0)$ which gives $r_2=.7\pm.2$. In the exclusive data sample four candidates have been found, two in the $\gamma\gamma\mu\mu$ and two in the $\gamma\gamma ee$ samples, which are consistent with the reaction $\Upsilon''\rightarrow\gamma\chi_b\rightarrow\gamma\gamma\Upsilon$. This gives an upper limit (90% CL) for the product branching ratio of $BR(\Upsilon''\rightarrow\gamma\chi_b)\times BR(\chi_b\rightarrow\gamma\Upsilon)<1.3\%$.

In the preceeding sections we have seen that potential models give a rather successful description of the $b\bar{b}$ bound states:

- Most potential model predictions for masses of the radially excited 3S_1 states, cog's of 3P states and leptonic widths are in reasonable agreement with the experimental data. The best predictions, however, are given by models that are most explicitly based on QCD--as e.g. the BT model--or that additionally include spin-independent relativistic corrections, like the Gupta or MR models.
- On the other hand, predictions from QCD sum rules or bag model calculations for the cog's of 3P states are inconsistent with measurements.
- The predicted E1 transition rates are on the average slightly lower than the measured values. However, due to large experimental uncertainties, we consider predicted and measured rates not to be inconsistent.
- The experimental data favor a scaling of α_s according to perturbative QCD as indicated by the observation of a small fine splitting ΔE_{FS} .

the spin-orbit and tensor interactions in the $b\bar{b}$ system [Ei 83].

--Find the 3P_0 states in the exclusive decay channels.

First a signal for the 3P_0 state in the lower energy photon spectrum allows to cross-check the position of the third line in the inclusive photon spectra reducing the systematic errors on the absolute energy scale. Second, from the product branching ratios in conjunction with the inclusive branching fractions one can evaluate $BR(n^3P_0 \rightarrow \gamma^3n'^3S_1)$. Using eq. (5.8a) one can in turn determine α_s and the QCD scale parameter $\Lambda_{\overline{MS}}$. This determination of $\Lambda_{\overline{MS}}$ is expected to be accurate since the ratio of hadronic widths $\Gamma(2^{++} \rightarrow 2g)/\Gamma(0^{++} \rightarrow 2g)$ can be calculated reliably in higher order QCD.

--Measure the angular distributions for the exclusive cascades.

This provides an experimental determination of the total spins of the 3P_J states. The angular distributions for the polar angle of the lower energy photon with respect to the initial electron are very suited for these measurements, since the coefficients in the $\cos^2\theta$ term of 1, -1/3, and 1/13 for transitions via $J=0, 1$, and 2 3P_J states are sufficiently different to be distinguishable in measurements. However, both large acceptances and high statistics are required. For example, in the present measurements both the statistics is too small and the acceptance is not large enough to determine the angular distributions unambiguously.

--Study the exclusive transition $T'' \rightarrow \gamma\chi_b \rightarrow \gamma\gamma T \rightarrow \gamma\gamma(e^+e^- \text{ or } \mu^+\mu^-)$.

Measuring the product branching ratios allows to determine $BR(T \rightarrow \gamma\chi_b)$ and in turn the overlap integral between the 2^3S_1 and 1^3P_J states. This provides another powerful test of potential models, since predictions for $BR(T'' \rightarrow \gamma\chi_b)$ vary from 0.04% [BT 81] to 5% [Ei 80].

--Find the 1^1P_1 state.

The 1^1P_1 state, which has not been found in charmonium, is predicted to be produced in the transition $T'' \rightarrow \pi^+\pi^-1^1P_1$ with a branching ratio of $\sim 1\%$ [KY 81]. One therefore expects to observe a signal in the $\pi^+\pi^-$ missing mass spectrum. Once the mass $M(1^1P_1)$ is measured the hyperfine splitting can be determined which allows to study the spin-spin interactions in the $b\bar{b}$ -system testing various predictions. Measuring the branching ratios provides another test of the multipole expansion model for soft gluons. In addition this transition is very suited to search for the η_b , as shown in fig. 5.8. Tagging both pions and cutting on the photon energy allows to reduce the hadronic background substantially.

--Study gluon jets in hadronic decay modes of the 3P states.

Because of the gluon self coupling, gluon jets are expected to be broader

- The predicted fine splittings ΔE_{FS} are on the average higher than the observed values.
- The measured ratios of level spacings r_n , which are independent of α_s and therefore much more suited for a comparison with predictions are at the present state not precise enough to draw definitive conclusions. Both r_1 and r_2 are consistent with predictions of 1.0 and of ~ 0.7 . Thus the flux tube model is as good as the EF model. However according to the measurement for r_1 of 1.0 ± 0.1 , values < 0.6 seem to be unlikely.
- Measurements indicate that the $q\bar{q}$ potential is nearly logarithmic in the range of 0.2 to 1.0 fm and is in fact flavor independent, as predicted by all models.

To put further constraints onto these models one needs first a better accuracy of the presently measured quantities. Second, one has to study other observables in the $b\bar{b}$, as for example the hyperfine splitting and fine splitting of 3D states. However, though all potentials are nearly identical in the range of .2 to 1.0 fm where the T and ψ states are located they differ substantially at smaller distances (< 0.1 fm). The study of the toponium system will provide a more discriminative test. For $m_t = 30$ GeV the 3S_1 ground state has a radius of $\langle r^2 \rangle^{1/2} = 0.07$ fm. Once toponium is discovered a measurement of Γ_{ee} for the ground state would be a straight-forward test of various models.

V.5 Outlook for Future Measurements on P States in Bottomonium

For a complete experimental study of the P-states in the $b\bar{b}$ system additional measurements are required:

- Remeasure the 2^3P_J states.

First the individual lines in the photon spectra have to be resolved to confirm our measurements on the λ_b' masses. Second the branching ratios for inclusive λ_b' production have to be measured with better accuracy to set tight constraints on the E1 transition rates. Third the product ratios of the exclusive cascade decays have to be measured more accurately to enable a precise determination of the branching fractions for $2^3P_J \rightarrow \gamma n^3S_1$, which in turn allows one to derive α_s (see point 4).

- Measure the fine splitting of both 1^3P_J and 2^3P_J states to better than 2%. This will set rather tight limits on the ratios r_n of level spacings, providing a powerful test of the various models on the spin-orbit and tensor interactions in the $b\bar{b}$ system. If in addition the fine splitting of the 3D states is measured one can determine experimentally the range of

than quark jets. The two gluon decays of the 3P_2 and 3P_0 states are the best source besides toponium decays for the study of gluon jets for several reasons. First the two gluon jets being back-to-back have nearly the same energy as light $q\bar{q}$ jets from the continuum. Therefore a direct comparison is possible. Second, for energies of 5 GeV per jet both gluon jets are already collimated such that they can be clearly identified. This is not the case for gluon jets from $\psi \rightarrow 3g$ and $T \rightarrow 3g$ decays. On the other hand, the energy is not too high, so individual particles in a jet can be resolved, allowing one to measure multiplicities, identify individual particles, and study substructures in a jet. In addition the 2 gluon decays are the dominant decay modes of the 3P_2 and 3P_0 states. Since the E1 transition rates are relatively large, one expects a rather large and clean sample of 2 gluon jet events. However, photon tagging is necessary in order to reduce the background from hadronic T' or T'' decays.

--Study electromagnetic decay modes of the 3P states.

Besides the transitions $n^3P_J \rightarrow \gamma n'^3S_1$ the 2^3P_J can in addition decay via the emission of a photon into the 3D_J states (see fig.2.8). The photons are expected at energies of ~ 100 MeV, the transition rates at the order of a few keV. Since the 3D_J states decay to 30-50% into $\pi\pi T$ the exclusive cascades $T'' \rightarrow \gamma \chi_b' \rightarrow \gamma\gamma^3D_J \rightarrow \gamma\gamma\pi\pi(T \rightarrow e^+e^- \text{ or } \mu^+\mu^-)$ provide promising transitions to find the 3D states and measure their fine splitting. Other interesting electromagnetic decay modes are $^3P_2(^3P_0) \rightarrow 2\gamma$ and $^3P_1 \rightarrow 3\gamma$. Again the monochromatic photons from the E1 transitions could be used for tagging. Measuring the branching ratios for $^3P_2(^3P_0) \rightarrow \gamma\gamma$ allows for an additional accurate determination of α_s , since the ratio $[\Gamma(2^{++} \rightarrow 2\gamma) / \Gamma(2^{++} \rightarrow \text{hadrons})] / [\Gamma(0^{++} \rightarrow 2\gamma) / \Gamma(0^{++} \rightarrow \text{hadrons})]$ is calculated reliably in higher order QCD.

However, in order to perform all these measurements successfully one needs both high luminosity and new detectors with good energy resolution for electromagnetic showers ($< 2\%$ at 100 MeV), good momentum resolution for charged particles and an acceptance close to 4π . In addition the calorimeter must be good enough to reconstruct π^0 's with a high efficiency.

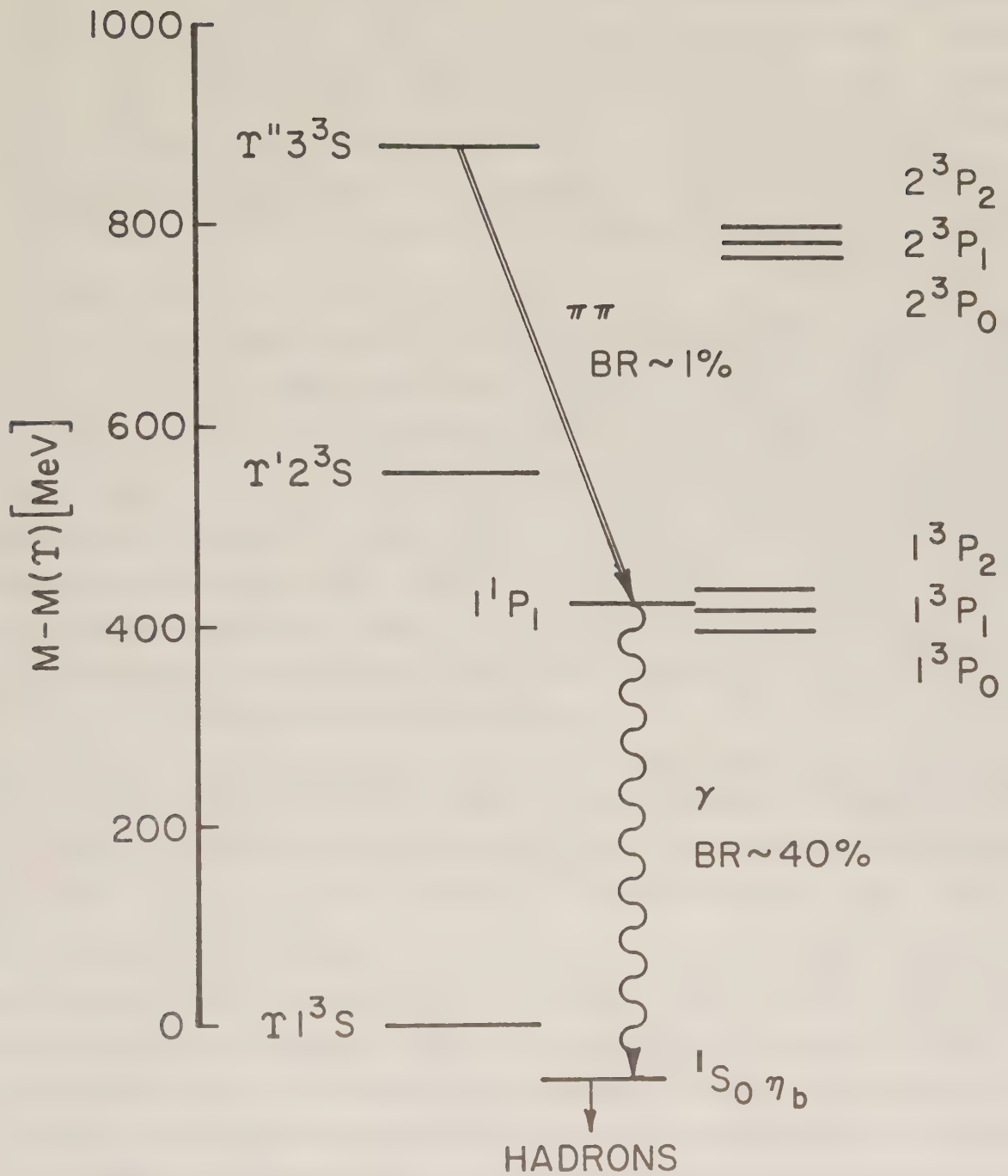


Fig. 5.8 A level diagram showing the transition $T'' \rightarrow \pi\pi 1^1P_1 \rightarrow \pi\pi\gamma\eta_b$.

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giving: +)

$$\begin{aligned} [\Gamma_{ggg}(n) + \Gamma_{\gamma gg}(n)]/\Gamma_{ee}(n) &= [\Gamma_{ggg}(T) + \Gamma_{\gamma gg}(T)]/\Gamma_{ee}(T) \\ &= [1/B_{\mu\mu}(T)] - 3 - R \end{aligned} \quad (A.5)$$

Using the measured branching ratios B_i , both $\Gamma_{tot}(n)$ and the individual partial widths Γ_i can be determined from eq. (A.4) where $\Gamma_i(n) = \Gamma_{tot}(n) \cdot B_i(n)$. The individual values are also listed in table A.1.

In chapter II we have used the identity:

$$\Gamma_{had}/\Gamma_{tot} = 1 - 3B_{\mu\mu} \quad (A.6)$$

For the T this follows straight forward from eqs. (A.1) and (A.2) since the hadronic width is given by:

$$\Gamma_{had}(T) = \Gamma_{ggg}(T) + \Gamma_{q\bar{q}}(T) + \Gamma_{\gamma gg}(T) \quad (A.7)$$

For the radially excited states additional hadronic events are produced in decays following $E1$ or $\pi\pi$ transitions, i.e. from $n^3S_1 \rightarrow \gamma m^3P_J \rightarrow \gamma + \text{hadrons}$, $n^3S_1 \rightarrow \gamma m^3P_J \rightarrow \gamma \gamma n'^3S_1 \rightarrow \gamma \gamma + \text{hadrons}$ and $n^3S_1 \rightarrow \pi \pi n'^3S_1 \rightarrow \pi \pi + \text{hadrons}$. Since these decay modes are the dominant contributions to Γ_{E1} and $\Gamma_{\pi\pi}$ -- ~97% for T' and ~98.5% for T'' decays -- Γ_{had} for the radially excited states is given to a good approximation by:

$$\Gamma_{had}(n) \approx \Gamma_{ggg}(n) + \Gamma_{q\bar{q}}(n) + \Gamma_{\gamma gg}(n) + \Gamma_{E1}(n) + \Gamma_{\pi\pi}(n) \quad (A.8)$$

Inserting eq. (A.8) into eq. (A.3) finally gives eq. (A.6).

For the 3P states the decomposition of Γ_{tot} into partial width is given by:

$$\Gamma_{tot}(n^3P_J) = \Gamma_{E1}(n^3P_J) + \Gamma_{had}(n^3P_J) \quad (A.9)$$

While to $\Gamma_{E1}(1^3P_J)$ only the transition $1^3P_J \rightarrow \gamma 1^3S_1$ contributes, $\Gamma_{E1}(2^3P_J)$ has contributions from $2^3P_J \rightarrow \gamma 2^3S_1$, $2^3P_J \rightarrow \gamma 1^3S_1$ and $2^3P_J \rightarrow \gamma 1^3D_J'$. However the rates $\Gamma_{E1}(2^3P_J \rightarrow \gamma 1^3D_J')$ are expected to contribute to Γ_{E1} only at the 10% level [Ei 80]. The hadronic widths of the $J=0$ and $J=2$ 3P states

+) This follows directly from eqs. (2.19) and (2.21) and the ratio $\Gamma_{ggg}/\Gamma_{\gamma gg} = (5/36)(a_s/(a \cdot e_b^2))[1 - 2.2a_s/\pi]$.

APPENDIX A

Partial and Total Widths of $b\bar{b}$ Bound States

The processes contributing to the total widths of the narrow Υ states have been shown in fig. 2.3. For the Υ , the decomposition of Γ_{tot} in terms of partial widths is simply given by:

$$\Gamma_{\text{tot}}(\Upsilon) = \Gamma_{\text{ggg}}(\Upsilon) + \Gamma_{11}(\Upsilon) + \Gamma_{q\bar{q}}(\Upsilon) + \Gamma_{\gamma\text{gg}}(\Upsilon) \quad (\text{A.1})$$

where the individual components denote the rates for decays into 3 gluons, lepton pairs, $q\bar{q}$ pairs and a photon plus two gluons, respectively.

Defining $R := \sigma(e^+e^- \rightarrow \text{hadrons}) / \sigma(e^+e^- \rightarrow \mu^+\mu^-)$ and using lepton universality one obtains $\Gamma_{q\bar{q}} = R \cdot \Gamma_{ee}$ and $\Gamma_{11} = 3\Gamma_{ee}$ which in turn gives:

$$\Gamma_{\text{tot}}(\Upsilon) = \Gamma_{\text{ggg}}(\Upsilon) + (3+R)\Gamma_{ee}(\Upsilon) + \Gamma_{\gamma\text{gg}}(\Upsilon) \quad (\text{A.2})$$

From measuring $B_{\mu\mu}(\Upsilon)$, $\Gamma_{ee}(\Upsilon)$, and R one can determine $\Gamma_{\text{tot}}(\Upsilon)$ and $\Gamma_{\text{ggg}}(\Upsilon) + \Gamma_{\gamma\text{gg}}(\Upsilon)$ from eqs. (A.2) and (2.5a). The values derived by this method are listed in table A.1, where the world average of $R = 3.63 \pm 0.14$ at $E_{\text{CM}} \approx 10$ GeV has been used. Measurements for R versus the CM energy are plotted in fig. A.1.

For the radially excited Υ resonances Γ_{tot} has additional contributions from the $\pi\pi^-$ and $E1$ -transitions $n^3S_1 \rightarrow \pi\pi n'^3S_1$ and $n^3S_1 \rightarrow \gamma m^3P$, yielding:

$$\Gamma_{\text{tot}}(n) = \Gamma_{\text{ggg}}(n) + (3+R)\Gamma_{ee}(n) + \Gamma_{\gamma\text{gg}}(n) + \Gamma_{\pi\pi}(n) + \Gamma_{E1}(n) \quad (\text{A.3})$$

In principle, $\Gamma_{\text{tot}}(n)$ and $\Gamma_{\text{ggg}}(n) + \Gamma_{\gamma\text{gg}}(n)$ can again be determined from $B_{\mu\mu}(n)$, $\Gamma_{ee}(n)$ and the individual branching fractions $B_{\pi\pi}(n)$ and $B_{E1}(n)$. However, since $B_{\mu\mu}(n)$ is not well measured, a more accurate determination for the total widths is obtained by expressing $\Gamma_{\text{tot}}(n)$ in terms of $B_{\mu\mu}(\Upsilon)$, the branching fractions $B_{\pi\pi}(n)$, $B_{E1}(n)$ and the leptonic width $\Gamma_{ee}(n)$, yielding:

$$\Gamma_{\text{tot}}(n) = \Gamma_{ee}(n) / [B_{\mu\mu}(\Upsilon) (1 - B_{\pi\pi}(n) - B_{E1}(n))] \quad (\text{A.4})$$

This expression follows directly from eq. (A.2) if one uses the property that the ratio $[\Gamma_{\text{ggg}}(n) + \Gamma_{\gamma\text{gg}}(n)] / \Gamma_{ee}(n)$ is independent of $M(n)$ and $|\Psi_n(0)|$,

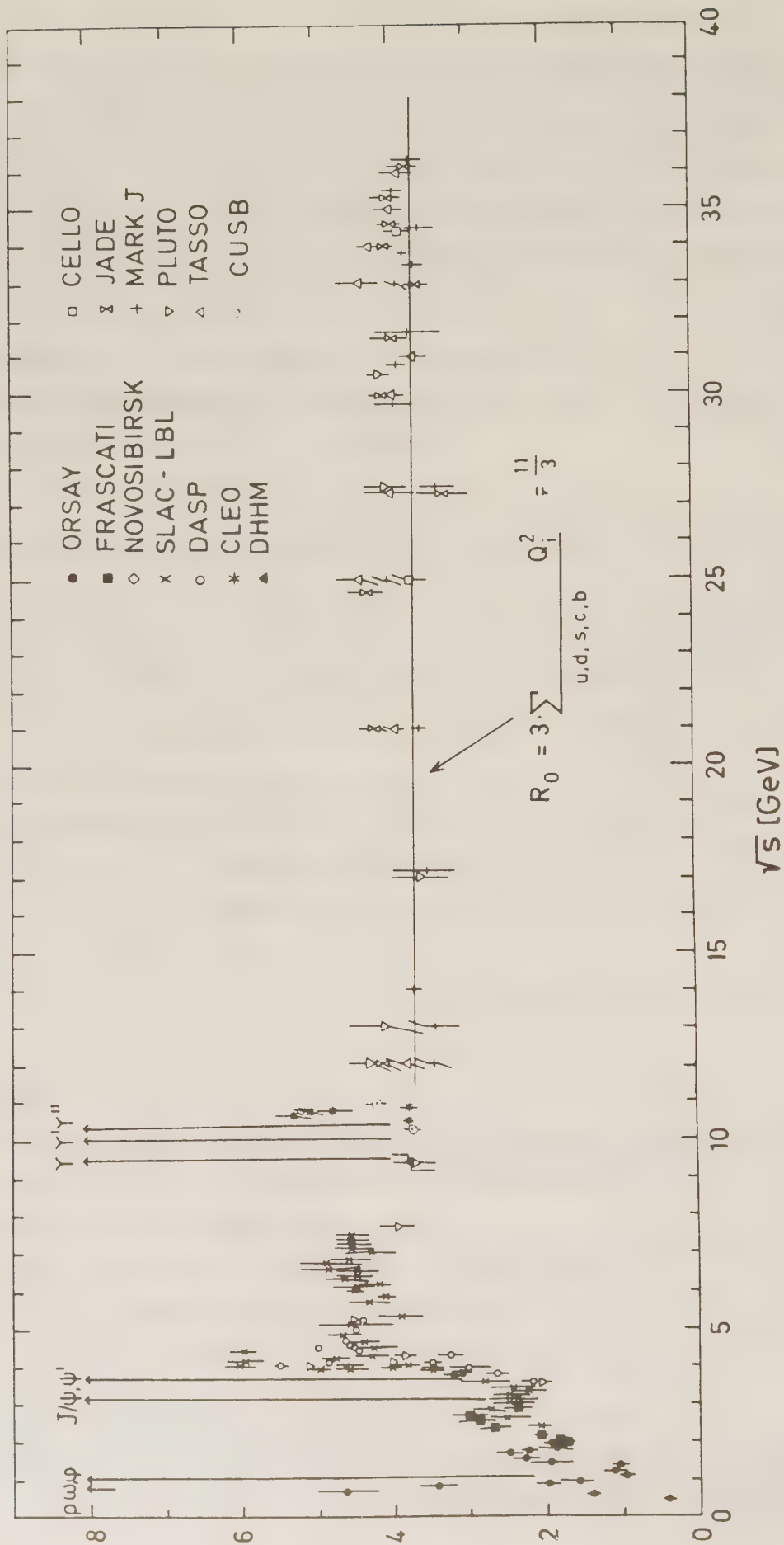


Fig. A.1 The ratio R of the total cross section for e^+e^- annihilation into hadrons to the μ pair cross section, $\sigma_{\mu\mu} = 4\pi\alpha^2/(3s)$. From [Fe 81] updated for CUSB data.

are essentially given by the two gluon annihilation, while $\Gamma_{\text{had}}(^3P_1)$ consists of the decay $^3P_1 \rightarrow gq\bar{q}$ with a small contribution from the 3 gluon annihilation. However, as discussed in V.2.5 these rates are not experimentally accessible with the present technology. $\Gamma_{\text{tot}}(n^3P_J)$ and $\Gamma_{\text{had}}(n^3P_J)$ can only be determined from the measured branching ratios for the E1 transitions if an additional theoretical prediction for Γ_{E1} is used. These estimates have been listed in Table 5.6 where contributions from $2^3P_J \rightarrow \gamma 1^3D_J$, have been neglected.

Table A.1 Partial and total widths of the T states.

Parameter	T	T'	T''
<u>Inputs</u>			
Γ_{ee} [keV]	$1.24 \pm .05$	$0.54 \pm .03$	$0.40 \pm .03$
$B_{\mu\mu}$ [%]	$2.90 \pm .20$	$1.90 \pm .60$	3.30 ± 1.5
$B_{\pi\pi}$ [%]		28.2 ± 1.5	$11.7 \pm 3.0^a)$
B_{E1} [%]		16.9 ± 2.1	35.9 ± 5.0
<u>Derived</u>			
Γ_{tot} [keV]	42.8 ± 3.4	33.9 ± 3.4	26.3 ± 4.0
$\Gamma_{ggg}^{b)}$ [keV]	34.6 ± 3.4	18.2 ± 3.7	11.1 ± 4.8
$\Gamma_{\pi\pi}$ [keV]		9.6 ± 1.2	3.1 ± 1.1
Γ_{E1} [keV]		5.7 ± 1.0	9.4 ± 2.5
$B_{\mu\mu}$ [%]		$1.59 \pm .15$	1.52 ± 0.2

All input values are averages over different experiments.

a) $B_{\pi\pi}$ has been obtained from the measured branching fractions $BR(T'' \rightarrow \pi^+\pi^-T) = (4.8 \pm 0.8)\%$ [Tu 83] and $BR(T'' \rightarrow \pi^+\pi^-T') = (3.0 \pm 1.9)\%$ [Ms 83] assuming isospin invariance.

b) Γ_{ggg} includes a $\sim 3\%$ contribution from $\Gamma_{\gamma gg}$. For the derivation we have used the experimental average for $R = 3.63 \pm .14$. At the T the ratio $\Gamma_{\gamma gg}/\Gamma_{ggg}$ was measured to $(2.37 \pm .24 \pm .18)\%$ [Sz 83] which in turn gives $\Gamma_{\gamma gg}(T) = 0.8 \pm .12$ keV.

also for polarized beams --.

In order to express the angular distributions in terms of polar coordinates we choose the lab-frame for convenience, which is defined such that the z_{lab} -axis is given by the initial e^- beam direction and the x_{lab} (y_{lab}) axis by the normal to the south (top) quadrant of our detector. If now θ_i and ϕ_i denote the corresponding polar and azimuth angles for the photons and the final $e^-(\mu^-)$ ($i=1,2,3$ for $\hat{k}', \hat{k}$ and $\hat{l}$) then the scalar products are simply given by:

$$\begin{aligned}\hat{n} \cdot \hat{k}' &= \cos\theta_1 & \hat{n} \cdot \hat{k} &= \cos\theta_2 & \hat{n} \cdot \hat{l} &= \cos\theta_3 \\ \hat{k} \cdot \hat{k}' &= \sin\theta_1 \sin\theta_2 \cos(\phi_2 - \phi_1) + \cos\theta_1 \cos\theta_2 \\ \hat{l} \cdot \hat{k}' &= \sin\theta_1 \sin\theta_3 \cos(\phi_3 - \phi_1) + \cos\theta_1 \cos\theta_3 \\ \hat{l} \cdot \hat{k} &= \sin\theta_2 \sin\theta_3 \cos(\phi_3 - \phi_2) + \cos\theta_2 \cos\theta_3\end{aligned}$$

Inserting these terms into eqs (B.1) one obtains after a few manipulations:

$$\begin{aligned}W_2 &= 81/320 \cdot [28/9 - 2/9 \cdot \cos^2\theta_1 + 1/3 \cdot \cos^2\theta_2 + 1/3 \cdot \cos^2\theta_3 + \cos^2\theta_1 \cos^2\theta_2 \\ &\quad + \cos^2\theta_1 \cos^2\theta_3 + 4/9 \cdot \cos^2\theta_2 \cos^2\theta_3 + 22/9 \cdot \cos^2\theta_1 \cos^2\theta_2 \cos^2\theta_3 \\ &\quad + \cos^2(\phi_2 - \phi_1) \cdot \sin^2\theta_1 \sin^2\theta_2 \cdot [1/3 + \cos^2\theta_3] \\ &\quad + \cos^2(\phi_3 - \phi_1) \cdot \sin^2\theta_1 \sin^2\theta_3 \cdot [1/3 + \cos^2\theta_2] \\ &\quad + 2/9 \cdot \cos^2(\phi_3 - \phi_2) \cdot \sin^2\theta_2 \sin^2\theta_3 \cdot [2\cos^2\theta_1 - 1] \\ &\quad + 2/3 \cdot \cos(\phi_2 - \phi_1) \cos(\phi_3 - \phi_1) \cos(\phi_3 - \phi_2) \cdot \sin^2\theta_1 \sin^2\theta_2 \sin^2\theta_3 \\ &\quad + 2/3 \cdot \cos(\phi_2 - \phi_1) \sin\theta_1 \cos\theta_1 \sin\theta_2 \cos\theta_2 \cdot [2 + 5\cos^2\theta_3] \\ &\quad + 2/3 \cdot \cos(\phi_3 - \phi_1) \sin\theta_1 \cos\theta_1 \sin\theta_3 \cos\theta_3 \cdot [2 + 5\cos^2\theta_2] \\ &\quad + 2/9 \cdot \cos(\phi_3 - \phi_2) \sin\theta_2 \cos\theta_2 \sin\theta_3 \cos\theta_3 \cdot [1 - 5\cos^2\theta_1] \\ &\quad - 2/3 \cdot \cos(\phi_2 - \phi_1) \cos(\phi_3 - \phi_2) \sin^2\theta_2 \sin\theta_1 \cos\theta_1 \sin\theta_3 \cos\theta_3 \\ &\quad - 2/3 \cdot \cos(\phi_3 - \phi_1) \cos(\phi_3 - \phi_2) \sin^2\theta_3 \sin\theta_1 \cos\theta_1 \sin\theta_2 \cos\theta_2 \\ &\quad + 8/3 \cdot \cos(\phi_2 - \phi_1) \cos(\phi_3 - \phi_1) \sin^2\theta_1 \sin\theta_2 \cos\theta_2 \sin\theta_3 \cos\theta_3] \quad (B.2a)\end{aligned}$$

$$\begin{aligned}W_1 &= 27/64 \cdot [4 - 2\cos^2\theta_1 - \sin^2\theta_1 (\cos^2\theta_2 + \cos^2\theta_3) + 2\cos^2\theta_1 \cos^2\theta_2 \cos^2\theta_3 \\ &\quad - [\cos^2(\phi_2 - \phi_1) + \cos^2(\phi_3 - \phi_1)] \cdot \sin^2\theta_1 \sin^2\theta_2 \sin^2\theta_3 \\ &\quad - 2\cos^2(\phi_3 - \phi_2) \cdot \sin^2\theta_2 \sin^2\theta_3 \\ &\quad + 2\cos(\phi_2 - \phi_1) \cos(\phi_3 - \phi_1) \cos(\phi_3 - \phi_2) \cdot \sin^2\theta_1 \sin^2\theta_3 \sin^2\theta_2 \\ &\quad + 2\cos(\phi_3 - \phi_1) \cos^2\theta_2 \sin\theta_1 \cos\theta_1 \sin\theta_3 \cos\theta_3 \\ &\quad + 2\cos(\phi_2 - \phi_1) \cos^2\theta_3 \sin\theta_1 \cos\theta_1 \sin\theta_2 \cos\theta_2 \\ &\quad - 2\cos(\phi_3 - \phi_2) \sin^2\theta_1 \sin\theta_2 \cos\theta_2 \sin\theta_3 \cos\theta_3 \\ &\quad + 2\cos(\phi_3 - \phi_2) \cos(\phi_2 - \phi_1) \sin^2\theta_2 \sin\theta_1 \cos\theta_1 \sin\theta_3 \cos\theta_3 \\ &\quad + 2\cos(\phi_3 - \phi_1) \cos(\phi_2 - \phi_1) \sin^2\theta_1 \sin\theta_2 \cos\theta_2 \sin\theta_3 \cos\theta_3 \\ &\quad + 2\cos(\phi_3 - \phi_2) \cos(\phi_3 - \phi_1) \sin^2\theta_3 \sin\theta_1 \cos\theta_1 \sin\theta_2 \cos\theta_2] \quad (B.2b)\end{aligned}$$

APPENDIX B

Angular Distributions for $e^+e^- \rightarrow n^3S_1 \rightarrow \gamma m^3P_J \rightarrow \gamma \gamma n'^3S_1 \rightarrow \gamma \gamma (e^+e^- \text{ or } \mu^+\mu^-)$

The angular distribution W_J for the transition $e^+e^- \rightarrow n^3S_1 \rightarrow \gamma m^3P_J \rightarrow \gamma \gamma n'^3S_1 \rightarrow \gamma \gamma (e^+e^- \text{ or } \mu^+\mu^-)$ in $q\bar{q}$ bound states have been calculated by Brown and Cahn [BC 75] in a cartesian representation using a pure dipole approximation for both photon transitions and assuming that the polarizations of the two photons and the final lepton pair remain unobserved. Here n, n' ($n > n'$), and m denote the principle quantum numbers of the $q\bar{q}$ system and $J=0, 1$, or 2 represents the total angular momentum of the 3P -states. If we further assume that the initial e^+e^- beams are unpolarized⁺ the angular distributions are given by:

$$\begin{aligned}
 W_2 = & 81/320 \cdot [[1+(\hat{k}' \cdot \hat{k})^2] [1+(\hat{n} \cdot \hat{l})^2] + [1+(\hat{k}' \cdot \hat{l})^2] [1+(\hat{n} \cdot \hat{k})^2] \\
 & + 4/9 \cdot [1+(\hat{k} \cdot \hat{l})^2] [1+(\hat{n} \cdot \hat{k}')^2] - 2/3 \cdot [(\hat{k}' \cdot \hat{k})^2 + (\hat{l} \cdot \hat{k})^2 + (\hat{l} \cdot \hat{k}')^2] (\hat{l} \cdot \hat{k}) (\hat{l} \cdot \hat{k}') (\hat{l} \cdot \hat{k}) (\hat{k}' \cdot \hat{k}) \\
 & - 1 + (\hat{n} \cdot \hat{l})^2 + (\hat{n} \cdot \hat{k}')^2 + (\hat{n} \cdot \hat{k})^2 - (\hat{n} \cdot \hat{k}') (\hat{n} \cdot \hat{k}) (\hat{k}' \cdot \hat{k}) \\
 & - (\hat{n} \cdot \hat{l}) (\hat{n} \cdot \hat{k}) (\hat{l} \cdot \hat{k}) - (\hat{n} \cdot \hat{l}) (\hat{n} \cdot \hat{k}') (\hat{l} \cdot \hat{k}') \\
 & + 2(\hat{n} \cdot \hat{l}) (\hat{n} \cdot \hat{k}) (\hat{l} \cdot \hat{k}') (\hat{k}' \cdot \hat{k}) - 4/3 \cdot (\hat{n} \cdot \hat{l}) (\hat{n} \cdot \hat{k}') (\hat{l} \cdot \hat{k}) (\hat{k}' \cdot \hat{k}) \\
 & - 4/3 \cdot (\hat{n} \cdot \hat{k}') (\hat{n} \cdot \hat{k}) (\hat{l} \cdot \hat{k}') (\hat{l} \cdot \hat{k})]] \quad (B.1a)
 \end{aligned}$$

$$\begin{aligned}
 W_1 = & 27/64 \cdot [[1+(\hat{n} \cdot \hat{k})^2] [1+(\hat{l} \cdot \hat{k}')^2] + [1+(\hat{n} \cdot \hat{l})^2] [1+(\hat{k}' \cdot \hat{k})^2] \\
 & - 2 [(\hat{k}' \cdot \hat{k})^2 + (\hat{l} \cdot \hat{k}')^2 + (\hat{l} \cdot \hat{k})^2 - (\hat{k}' \cdot \hat{l}) (\hat{k} \cdot \hat{l}) (\hat{k}' \cdot \hat{k}) - 1 + (\hat{n} \cdot \hat{l})^2 + (\hat{n} \cdot \hat{k}')^2 \\
 & + (\hat{n} \cdot \hat{k})^2 - (\hat{n} \cdot \hat{k}') (\hat{n} \cdot \hat{k}) (\hat{k}' \cdot \hat{k}) - (\hat{n} \cdot \hat{l}) (\hat{n} \cdot \hat{k}) (\hat{l} \cdot \hat{k}) \\
 & - (\hat{n} \cdot \hat{l}) (\hat{n} \cdot \hat{k}') (\hat{l} \cdot \hat{k}') + (\hat{n} \cdot \hat{l}) (\hat{n} \cdot \hat{k}) (\hat{l} \cdot \hat{k}') (\hat{k}' \cdot \hat{k})]] \quad (B.1b)
 \end{aligned}$$

$$W_0 = 9/16 \cdot [1+(\hat{n} \cdot \hat{k}')^2] [1+(\hat{l} \cdot \hat{k})^2] \quad (B.1c)$$

where

- $\hat{n}$: a unit vector along the direction of the initial e^- -beam.
- $\hat{l}$: a unit vector along the direction of the final e^- or μ^- .
- $\hat{k}'$: a unit vector along the direction of the first photon.
- $\hat{k}$: a unit vector along the direction of the second photon.

The normalization of the individual distributions has been chosen such that the average over all angles is unity. Note that the angular distributions are symmetric with respect to an interchange of $\hat{k}$ and $\hat{l}$ or $\hat{k}'$ and $\hat{n}$. -- The symmetry with respect to an interchange of $\hat{k}$ and $\hat{l}$ remains

⁺For normal running conditions at CESR (fixed lattice, short fills of ≤ 2 hours, CLEO magnet running) the polarization effect is $< 2\%$. At DORIS, however, the e^+e^- beams are up to 85% polarized.

For a finite detector geometry the integration of $W_J(\Omega)$ over all 6 angles yields:

$$I_2 = (567/640)\tilde{k} \cdot [1 - (1/21)a^2 + (11/189)b^2 + (11/189)c^2 + (11/567)a^2b^2 + (11/567)a^2c^2 - (1/63)b^2c^2 + (1/27)a^2b^2c^2] \quad (B.9a)$$

$$I_1 = (135/128)\tilde{k} \cdot [1 - (1/5)a^2 + (1/15)b^2 + (1/15)c^2 + (1/45)a^2b^2 + (1/45)a^2c^2 - (1/15)b^2c^2 + (1/27)a^2b^2c^2] \quad (B.9b)$$

$$I_0 = (27/32)\tilde{k} \cdot [1 + (1/3)a^2 - (1/9)b^2 - (1/9)c^2 - (1/27)a^2b^2 - (1/27)a^2c^2 + (1/9)b^2c^2 + (1/27)a^2b^2c^2] \quad (B.9c)$$

with:

$$\tilde{k} = a \cdot b \cdot c \cdot (\phi_1^{\max}/2\pi) \cdot (\phi_2^{\max}/2\pi) \cdot (\phi_3^{\max}/2\pi)$$

$$a := \cos\theta_1^{\max}, \quad b := \cos\theta_2^{\max}, \quad c := \cos\theta_3^{\max}$$

$\phi_i^{\max}$ and $\theta_i^{\max}$ denote the angular cutoffs of the fiducial volumes.

In order to determine the spin of the 3P_J states experimentally one has to measure these angular distributions. Best suited are the distributions for the lower energy photon with respect to the initial e^- direction, i.e. $\bar{W}_J(\theta_1)$, since the amplitudes in the $\cos^2\theta_1$ terms -- 1 for $W_0(\theta_1)$, -1/3 for $W_1(\theta_1)$ and 1/13 for $W_2(\theta_1)$ -- are sufficiently large to be distinguishable in measurements. However, eqs.(B.5a), (B.6a) and (B.7a) have to be corrected for the acollinearity of the final leptons, because in non-magnetic calorimeter detectors the charges of the e^+e^- or $\mu^+\mu^-$ pair cannot be observed.

$$\begin{aligned} W_0 = & 9/16 \cdot [1 + \cos^2 \theta_1] [1 + \sin^2 \theta_2 \sin^2 \theta_3 \cos^2 (\phi_3 - \phi_2) \\ & + \cos^2 \theta_2 \cos^2 \theta_3 + 2 \sin \theta_2 \cos \theta_2 \sin \theta_3 \cos \theta_3 \cos (\phi_3 - \phi_2)] \end{aligned} \quad (B.2c)$$

If the final leptons remain unobserved the angular distributions are obtained by averaging eqs.(B.1) over $\hat{l}$ or eqs.(B.2) over θ_3 and ϕ_3 , giving:

$$\bar{W}_2 = (3/80) \cdot [22 + 6(\hat{k} \cdot \hat{k}')^2 + 6(\hat{n} \cdot \hat{k})^2 + (\hat{n} \cdot \hat{k}')^2 + 3(\hat{n} \cdot \hat{k})(\hat{n} \cdot \hat{k}')(\hat{k} \cdot \hat{k}')] \quad (B.3a)$$

$$\begin{aligned} = & (3/80) \cdot [22 + \cos^2 \theta_1 + 6 \cos^2 \theta_2 + 9 \cos^2 \theta_1 \cos^2 \theta_2 + 6 \cos^2 (\phi_2 - \phi_1) \sin^2 \theta_1 \sin^2 \theta_2 \\ & + 15 \cos (\phi_2 - \phi_1) \sin \theta_1 \cos \theta_1 \sin \theta_2 \cos \theta_2] \end{aligned} \quad (B.4a)$$

$$\bar{W}_1 = (9/16) \cdot [2 - (\hat{n} \cdot \hat{k}')^2 + (\hat{n} \cdot \hat{k}')(\hat{n} \cdot \hat{k})(\hat{k} \cdot \hat{k}')] \quad (B.3b)$$

$$= (9/18) \cdot [2 - \cos^2 \theta_1 \sin^2 \theta_2 + \cos (\phi_2 - \phi_1) \sin \theta_1 \cos \theta_1 \sin \theta_2 \cos \theta_2] \quad (B.4b)$$

$$\bar{W}_0 = (3/4) \cdot [1 + (\hat{n} \cdot \hat{k}')^2] \quad (B.3c)$$

$$= (3/4) \cdot [1 + \cos^2 \theta_1] \quad (B.4c)$$

Averaging eqs.(B.4) over the azimuth angles ϕ_1, ϕ_2 and either θ_1 or θ_2 gives the distributions $\bar{W}_J(\theta_i)$ listed in eqs.(4.4-4.6):

$$\bar{W}_2(\theta_1) = 39/40(1 + (1/13) \cdot \cos^2 \theta_1) \quad (B.5a)$$

$$\bar{W}_2(\theta_2) = 73/80(1 + (21/73) \cdot \cos^2 \theta_2) \quad (B.5b)$$

$$\bar{W}_1(\theta_1) = 9/8(1 - (1/3) \cdot \cos^2 \theta_1) \quad (B.6a)$$

$$\bar{W}_1(\theta_2) = 15/16(1 + (1/5) \cdot \cos^2 \theta_2) \quad (B.6b)$$

$$\bar{W}_0(\theta_1) = 3/4(1 + \cos^2 \theta_1) \quad (B.7a)$$

$$\bar{W}_0(\theta_2) = 1 \quad (B.7b)$$

The distributions for $W_J(\theta_3)$ are identical to $W_J(\theta_2)$.

If only the angle between both photons $\theta_{\gamma\gamma}$ is observed one can take the average over $\hat{n}$ in eqs.(B.3), yielding:

$$\bar{W}_2 = (73/80) [1 + (21/73) \cdot (\hat{k} \cdot \hat{k}')^2] \quad (B.8a)$$

$$\bar{W}_1 = (15/16) [1 + (1/5) \cdot (\hat{k} \cdot \hat{k}')^2] \quad (B.8b)$$

$$\bar{W}_0 = 1 \quad (B.8c)$$

Defining a new coordinate system, where $\hat{k}'$ is parallel to z , one just obtains $\hat{k} \cdot \hat{k}' = \cos \theta_{\gamma\gamma}$.

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Finally, I would like to dedicate this thesis to my parents and my wife, for their devotion and support through the years.

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